Light Water Reactor Materials Issues

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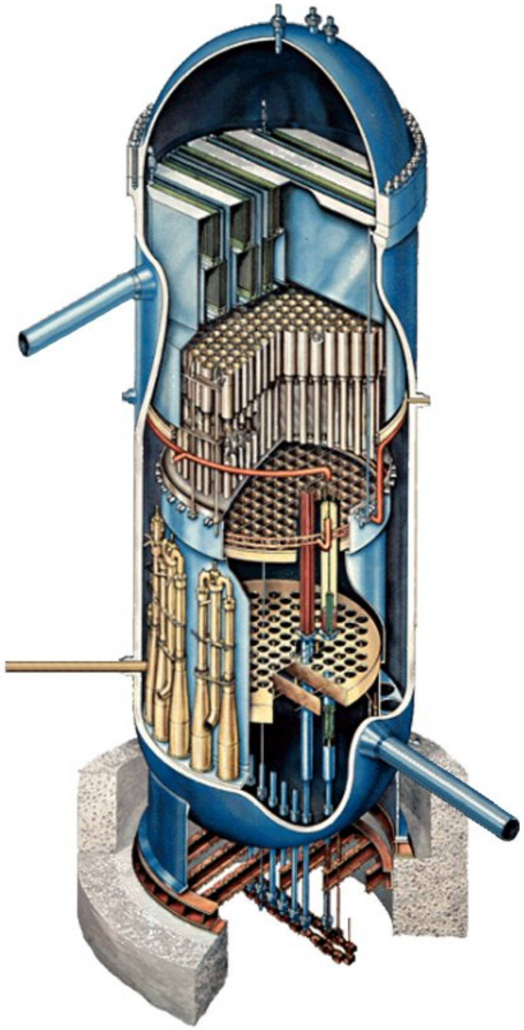
GE Global Research

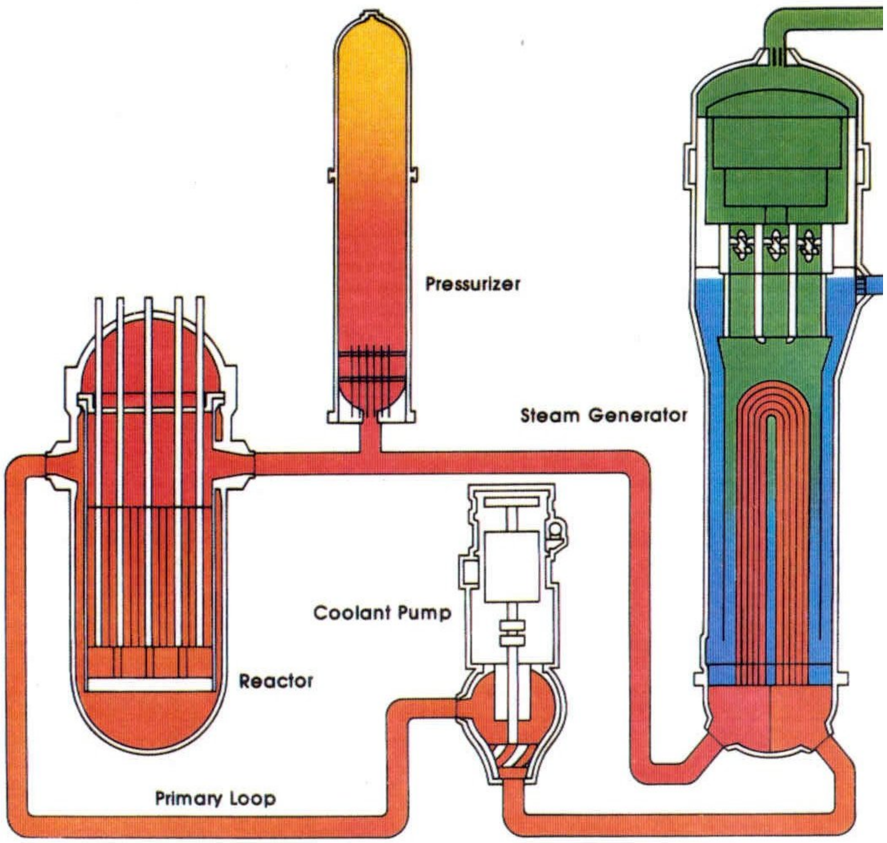
ATR NSUF Users Week

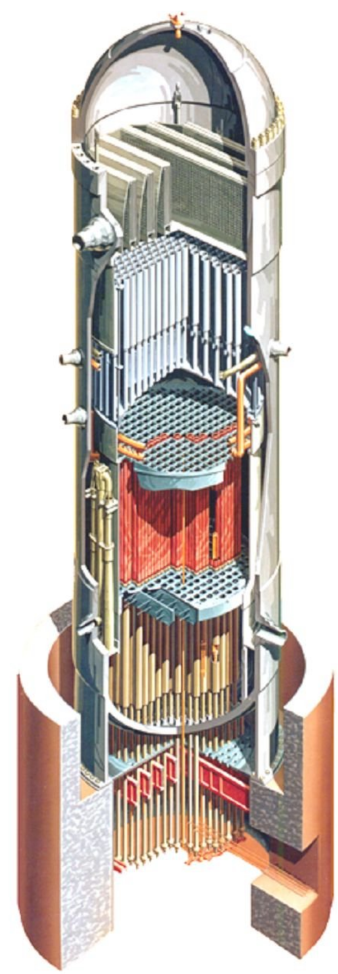
Overview

- Material Degradation Overview
- BWR vs. PWR Features
- BWR Major Internal Components
- BWR Evolution
- SCC In BWRs
- Material Processing Issues
- Crack Initiation
- ECP Monitoring & NobleChem™
- PWR Water Chemistry & Cracking Issu



Reactor Types in the US





Pressurized Water Reactor (PWR) **Boiling Water Reactor (BWR-6)**

Materials Degradation

- "MD" is a very broad description and widely applicable
  - Concrete, wire insulation, service water, roofing ….
- Forms of materials degradation can span:
  - Fracture toughness – radiation or environmental effects
  - Fatigue – thermal mixing, resonance, water hammer…
  - Stress corrosion cracking (~static load)
  - Corrosion fatigue (cyclic load)
  - Localized corrosion – pitting, crevice corrosion, IG attack
  - Flow assisted corrosion and erosion-corrosion
  - General corrosion
- Focus on structural materials used as pressure boundaries or vessel internal components

Historical View of Environmental Cracking

- discovered ductile Overload failure of metals (UTS)
- repeated loading to <50% UTS caused Fatigue failure
- fails in environment sooner – Corrosion Fatigue (CF)
- fails at constant load – Stress Corrosion Cracking (SCC) at progressively less aggressive environments & loads

The adequacy of design & live evaluation codes drops dramatically from Overload $\rightarrow$ Fatigue $\rightarrow$ CF $\rightarrow$ SCC

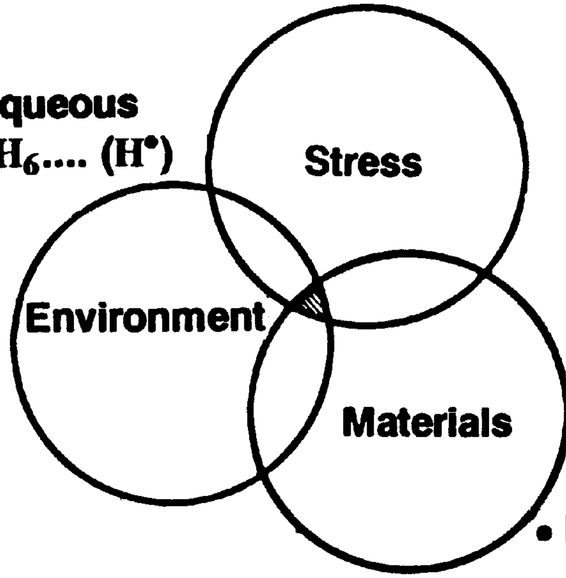
As designs account for fatigue and push to higher performance and longer lives, CF and SCC will increase

Solely-mechanics-based codes are inadequate

Broad View of Environmental Cracking

- Static & Dynamic (monotonic & cyclic)
- Cracking on Smooth Specimens at <1 ksi
- Range of frequency, ΔK, $\Delta\sigma$....

- Aqueous & non-aqueous
- Gaseous: H_2, C_2H_6.... ($H^{\bullet}$)
  - N_2O_4
  - Steam
  - O_2, Air ?
- Liquid Metals

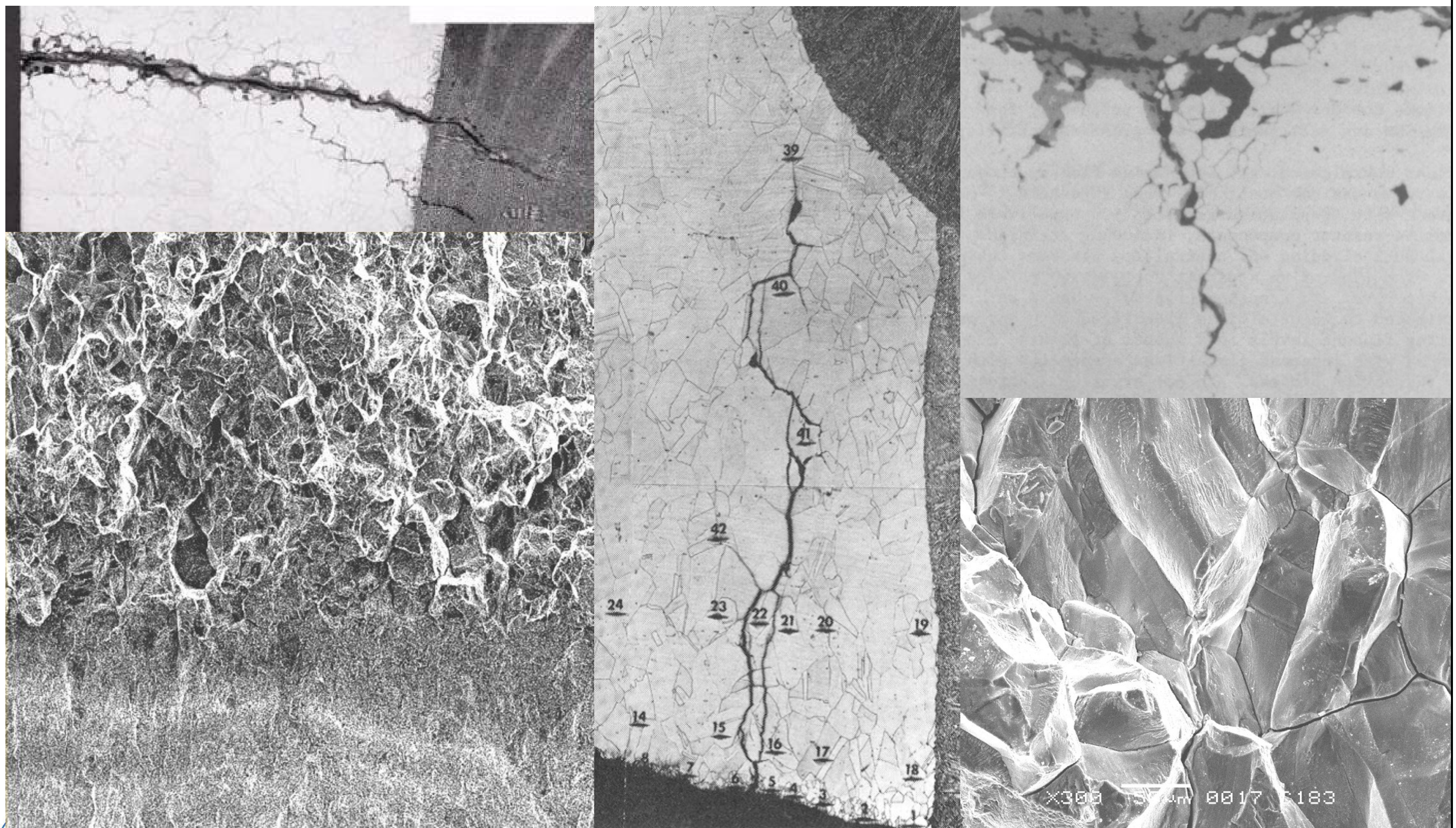


- Metallic & Non-metallic (glasses, plastics, ceramics)
- Crystalline & Amorphous
- High strength & Ductile
- Alloys & Pure Metals

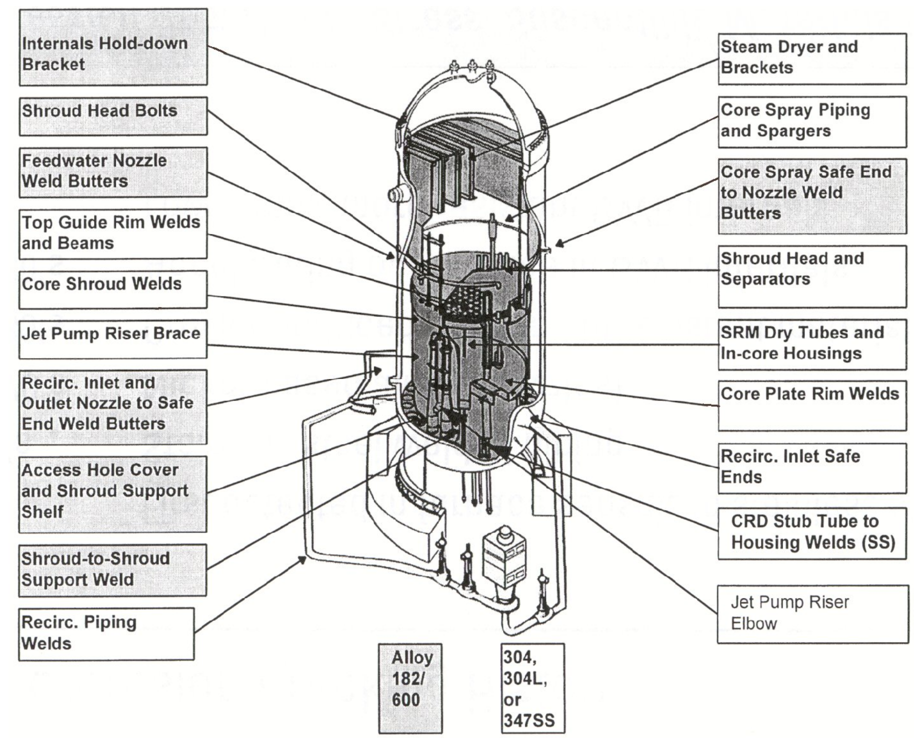
ENVIRONMENTAL CRACKING

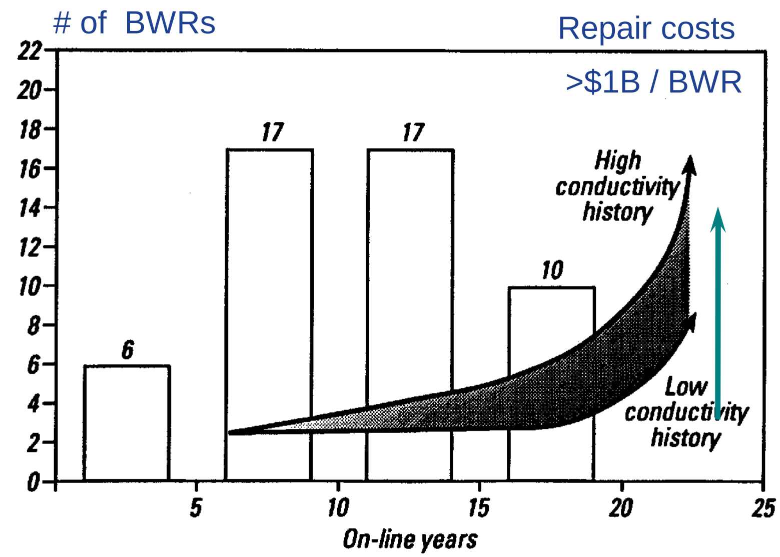
- Rates $<10^{-12}$ to 10^{0} m/s
- Stress Corrosion Cracking
- Corrosion Fatigue
- Hydrogen Embrittlement
- (Liquid Metal Embrittlement)
- (Environmental Creep-Fatigue)

SCC Occurs in Stainless Steels & Ni Alloys



BWR Sens. SS Piping → Core Components





Operating BWRs

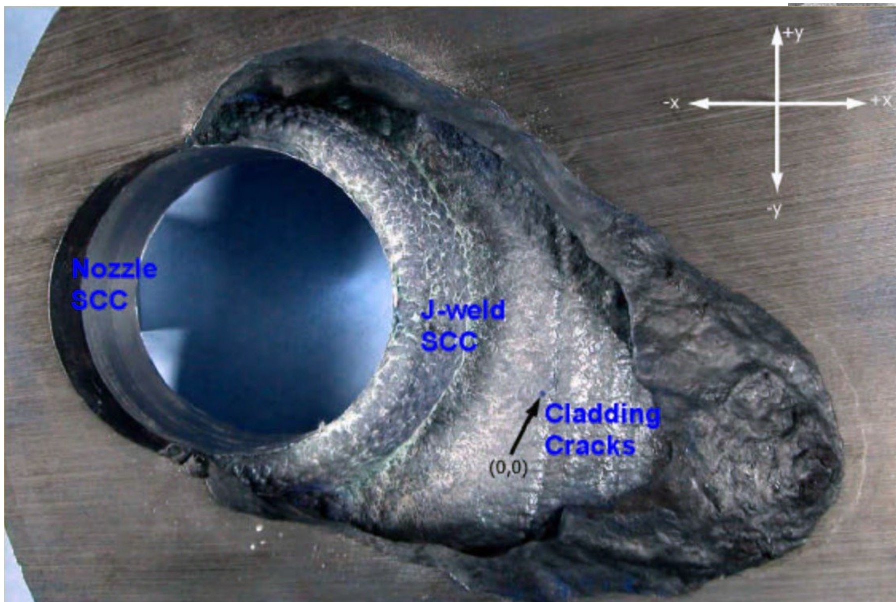
	N. America	Europe	Asia	Total
GE	36	4	11	51
Non-GE	0	16	21	38

80,000 MWe installed

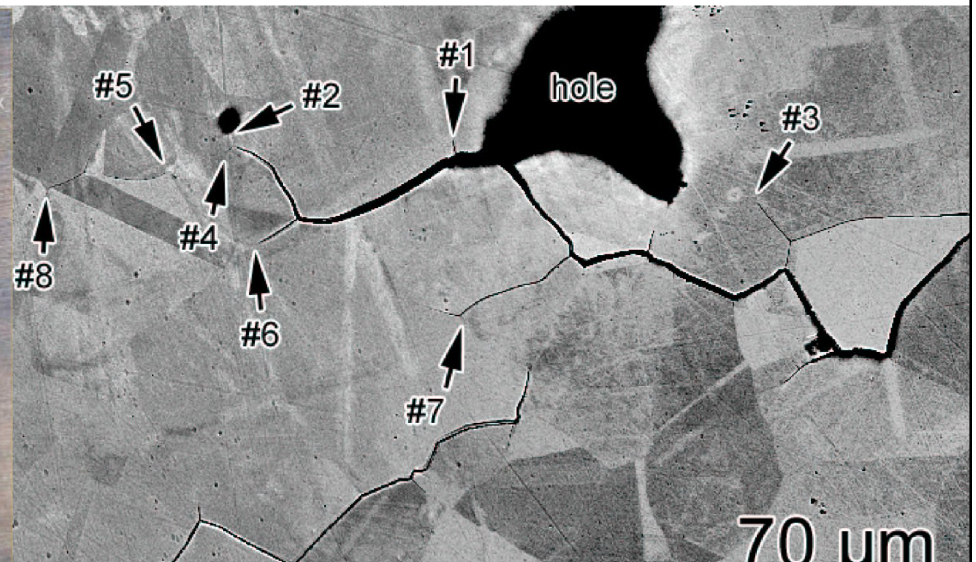
Stress Corrosion Cracking History

- 1969 1st detected in sensitized SS
- 1970s Stainless steel welded piping
- 1980s BWR internals
- 1990s Low stress BWR internals
  → NobleChem™ SCC mitigation

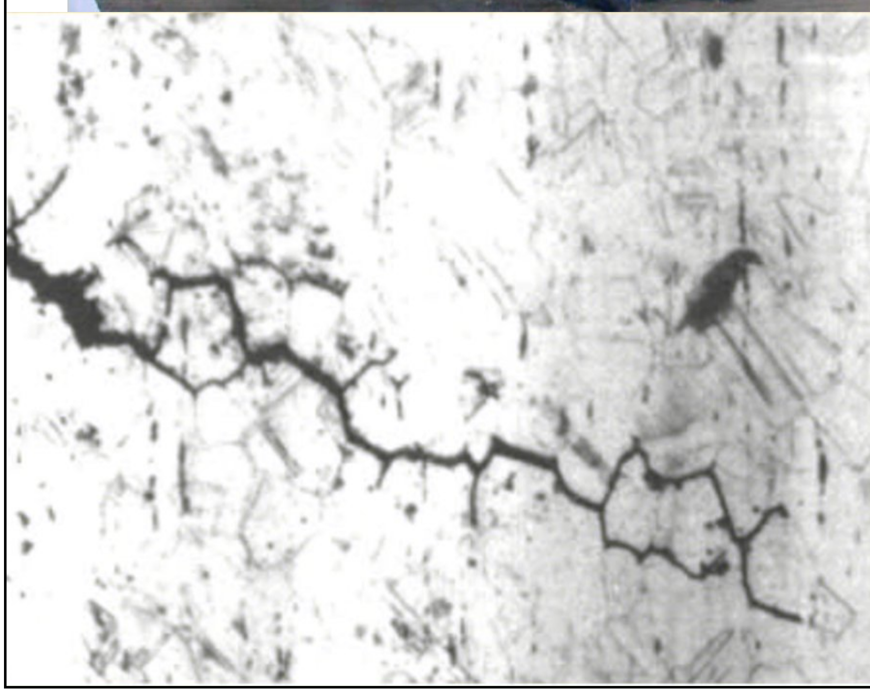
SCC in PWRs

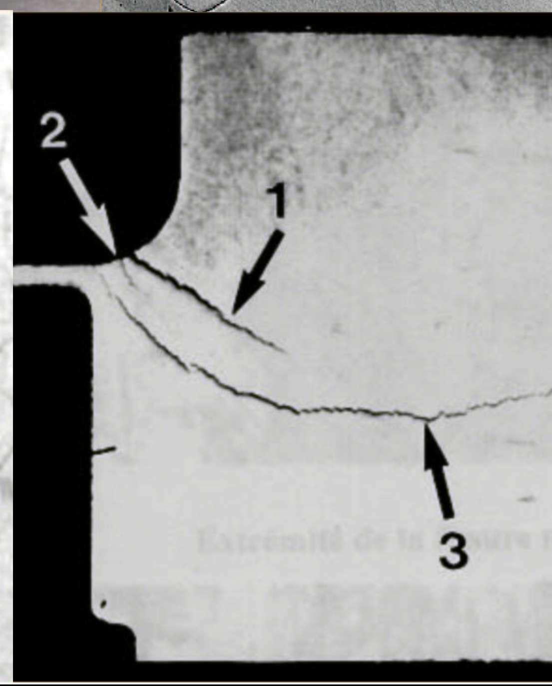


+y
-x
+x
-y
Nozzle SCC
J-weld SCC
Cladding Cracks
(0,0)

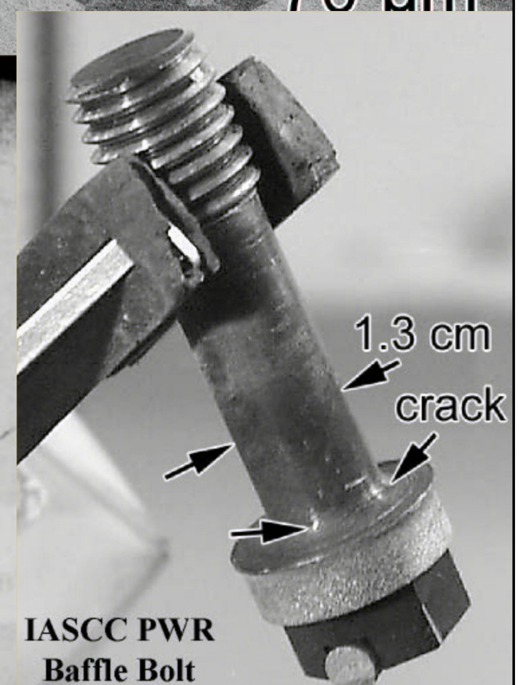


#1
hole
#5
#2
#3
#4
#8
#6
#7
70 µm



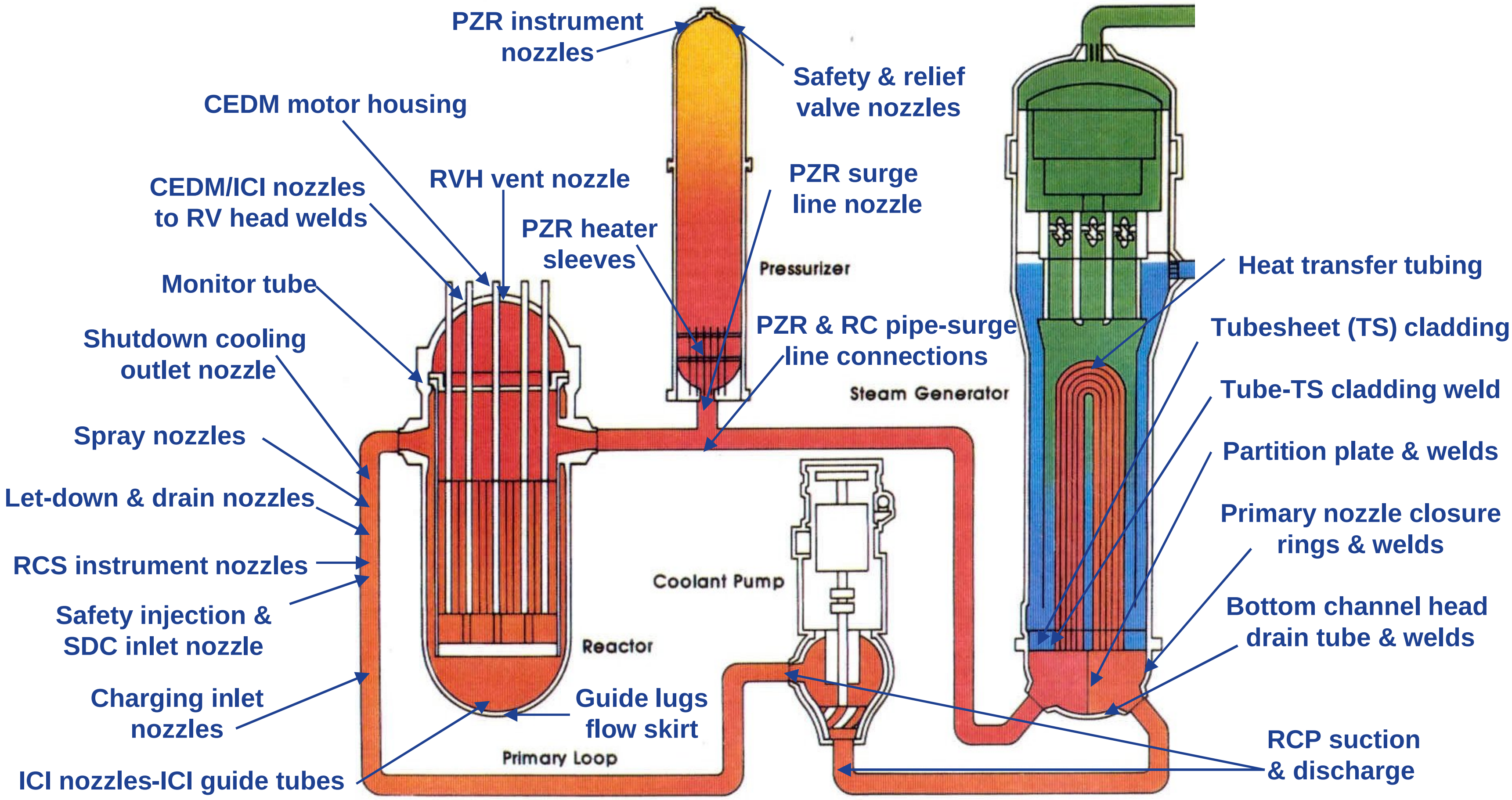


2
1
3



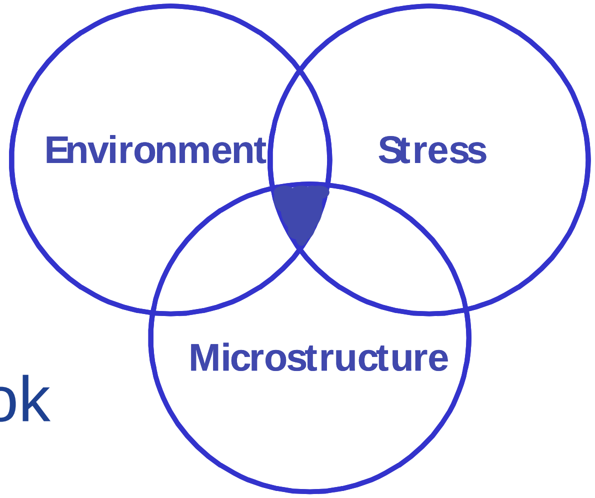
1.3 cm
crack
IASCC PWR Baffle Bolt

PWR Design (Shows A600/82/182 Use)



SS failures in O_2 stagnant areas: seals, check valves, etc. and in irradiated SS – concern for cracking in weld HAZs

Why Did Surprises Occur?



- Reliance on low temperature data (“stainless steel” ok in “pure water”)
- “Reasonable” assumption that <0.1 ppm levels of Cl & SO_4 would be ok
- Limited knowledge of weld sensitization and its importance in “pure water”
- Reliance on simple screening tests insensitive to low growth rates needed for 40 yr life
- Assumption of SCC immunity (from accelerated tests)
- Tendency to see failures as “unique”, not forewarning

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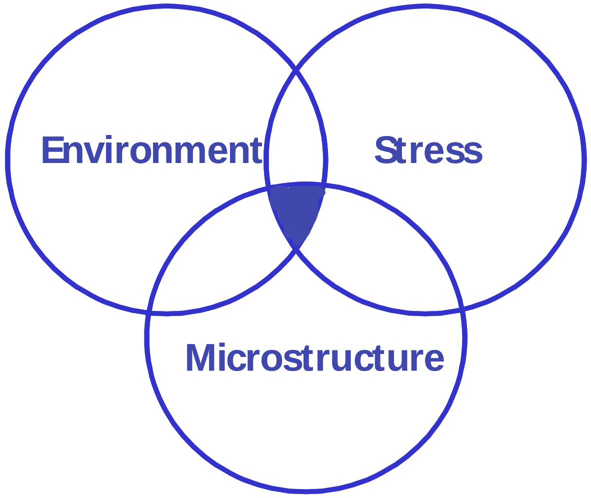
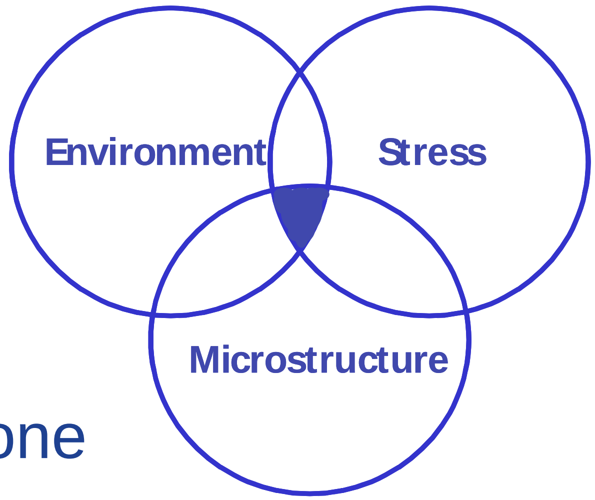


- Belated recognition of importance of:
  - sensitization (~1960 – 65)
  - cold work (~1965 – 69)
  - sensitivity to <10 ppb Cl/SO4 (~1980)
  - data quality & test techniques (~1990)
  - accelerated corr. fatigue at low potential (~1994)
  - weld residual strain (~1995)
  - high Si content & radiation segregation (~2000 - 01)
  - role of changing K vs. crack depth, dK/da (~2003)
  - environmental effect on fracture toughness (~2003)
- Loss of proactive or active response to emerging issues
- SCC is complex mix of metallurgy, mechanics, environment

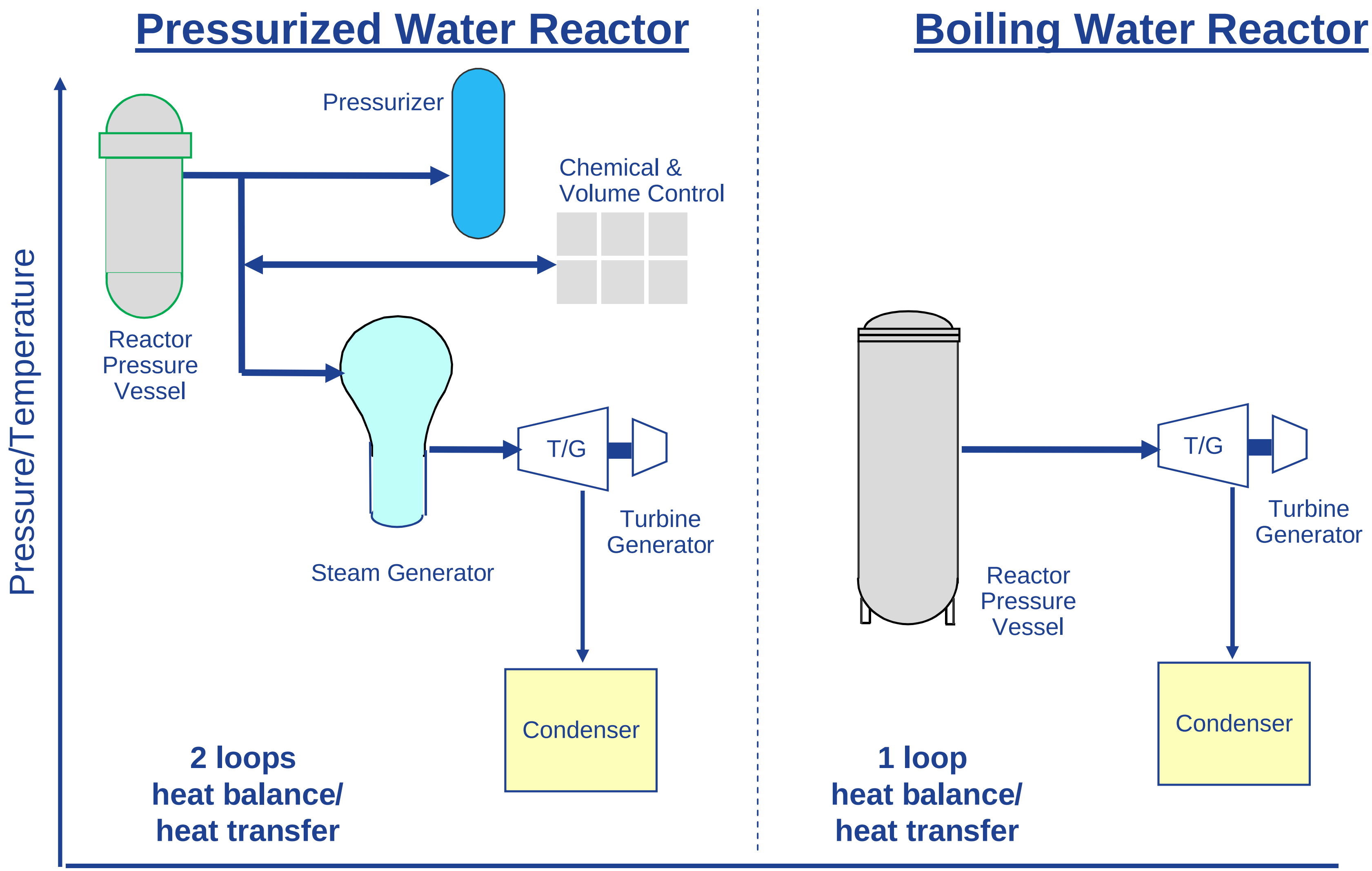
Engineering Factors in SCC



- Corrosion Potential (esp. oxidants)
- Water Purity – esp. Cl & SO4
- Yield Strength / Cold Work
  in bulk, surface or weld heat affected zone
- Stress Intensity Factor – and cycling / vibration
- Sensitization (grain boundary Cr depletion)
- Grain Boundary Carbides; Low Energy Boundaries
- Temperature & Temperature Gradients / Boiling
- Composition (Mo, Ti, Nb, low C, high N) not that
  important apart from decreasing sensitization

BWR vs. PWR

PWR and BWR… the main differences



Principle of Steam Generation

BWR

- RPV Pressure ~7 MPa (1020 psig)
- RPV Temperature 288 ºC (550 ºF)
- Steam Generated in RPV (with Separator & Dryer)
- Bulk Boiling Allowed in RPV

PWR

- RPV Pressure ~15 MPa (~2240 psig)
- RPV Temperature 326 ºC (~618 ºF)
- Steam Generated in Steam Generator (via Second Loop)
- No Bulk Boiling in RPV

BWR has Lower RPV Pressure and Simplified Steam Cycle

Major NSSS Components

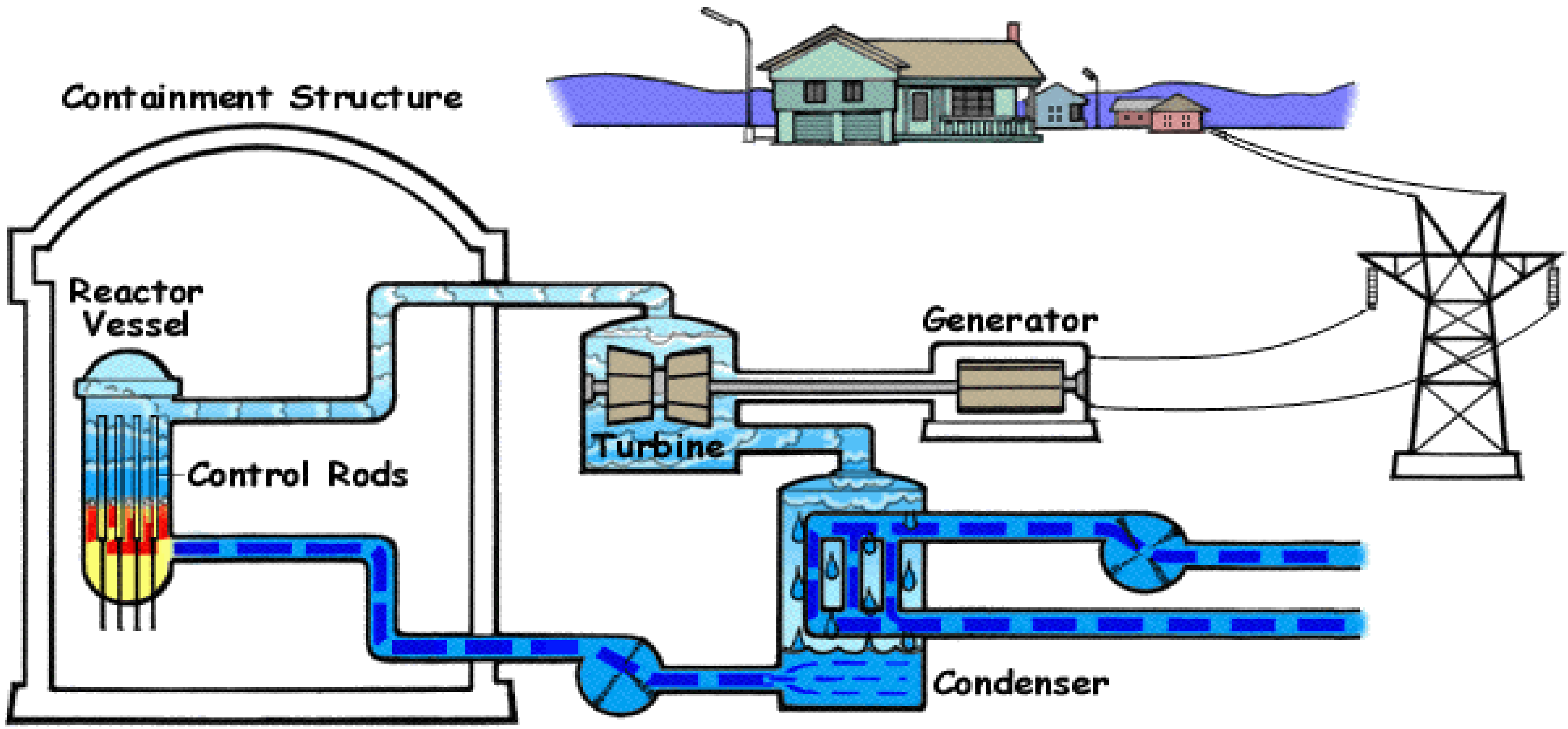
BWR

- RPV (with Dryer & Separator)
- No Steam Generator
- No Pressurizer
- Natural Circulation (ESBWR)
- RPV mounted pumps (ABWR)
- Bottom Entry Control Rod Drives

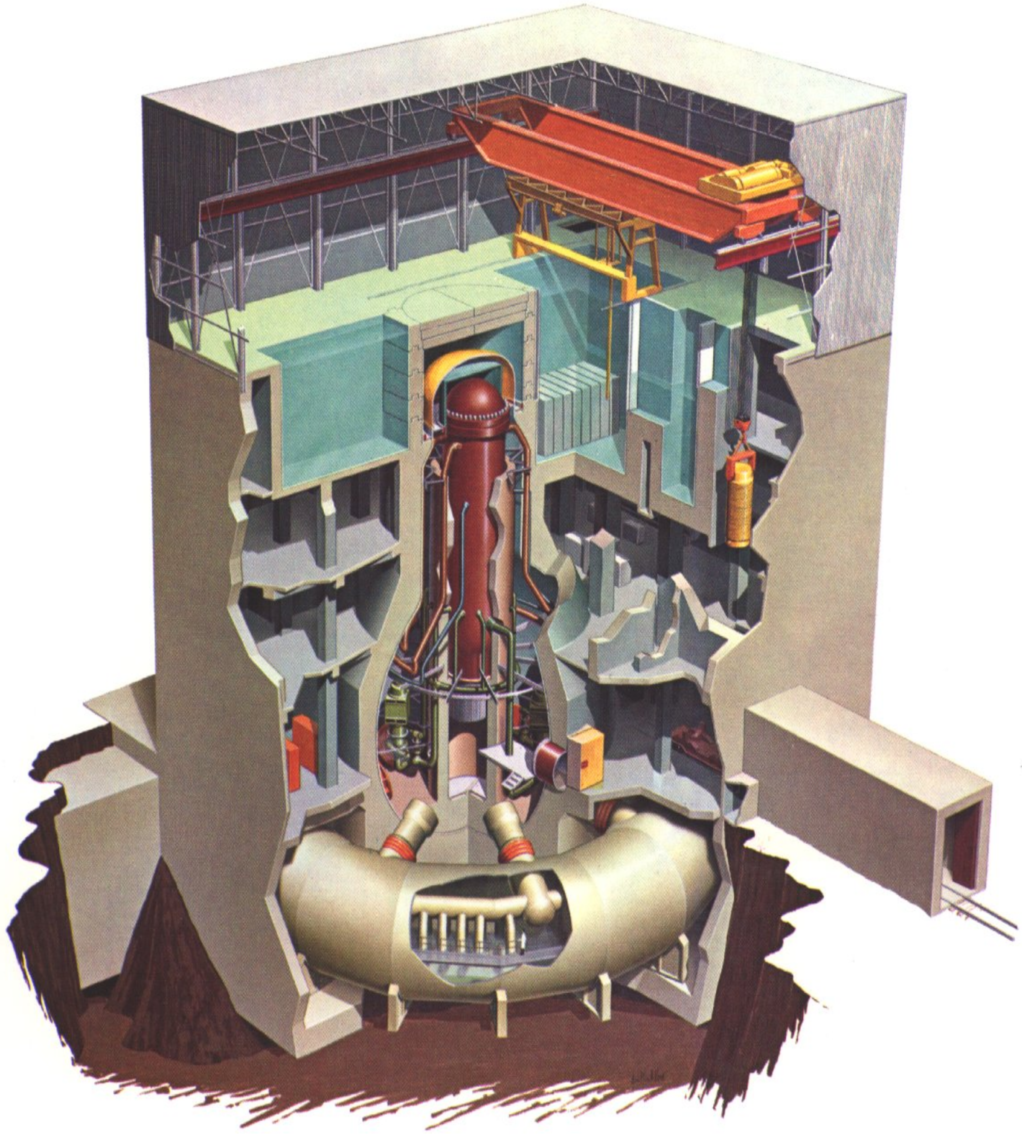
PWR

- RPV
- 2 - 4 Steam Generators
- 1 Pressurizer
- Reactor Coolant Pumps outside of RPV
- Top Entry Control Rod Clusters

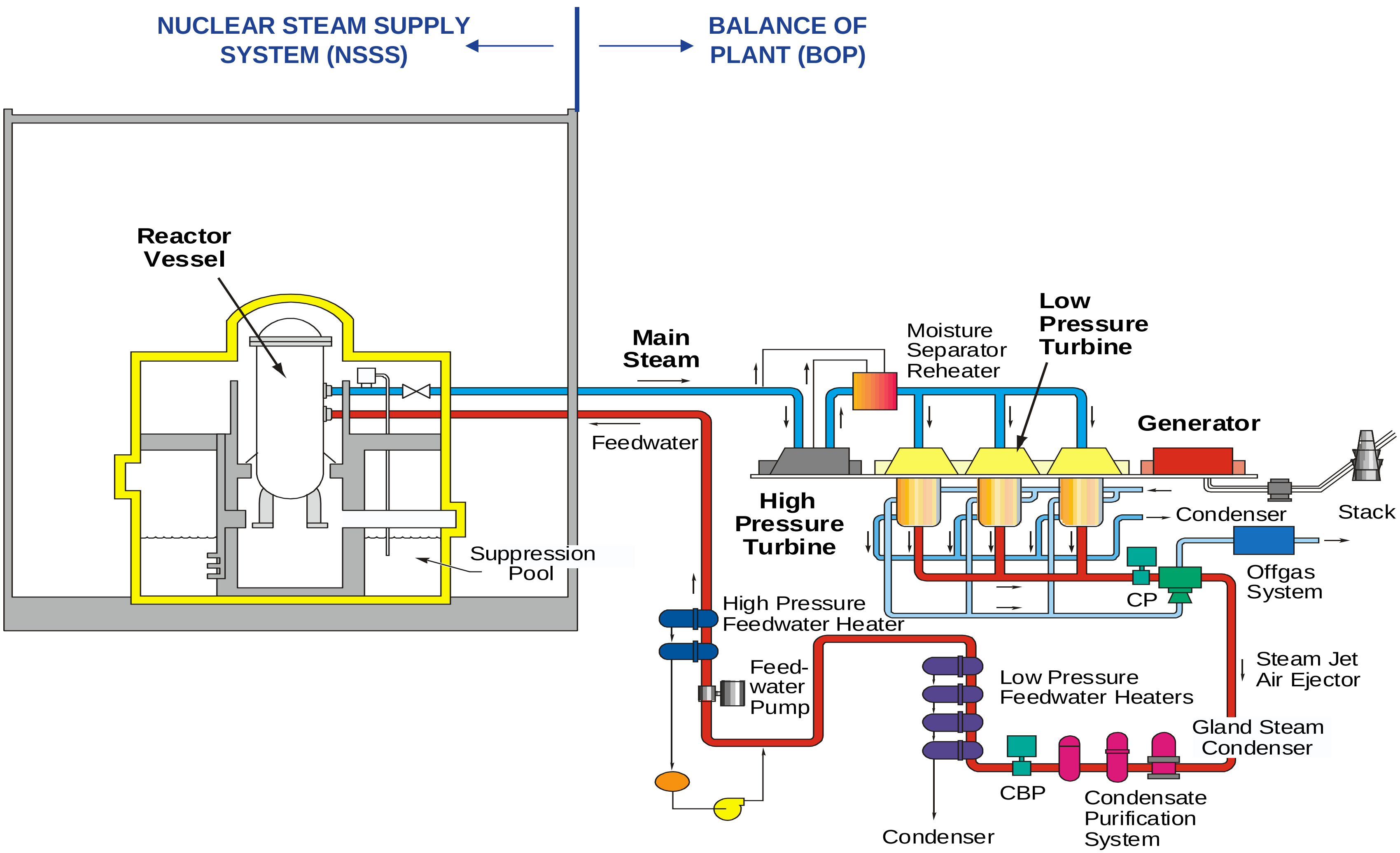
BWR Big Picture



BWR Primary Containment

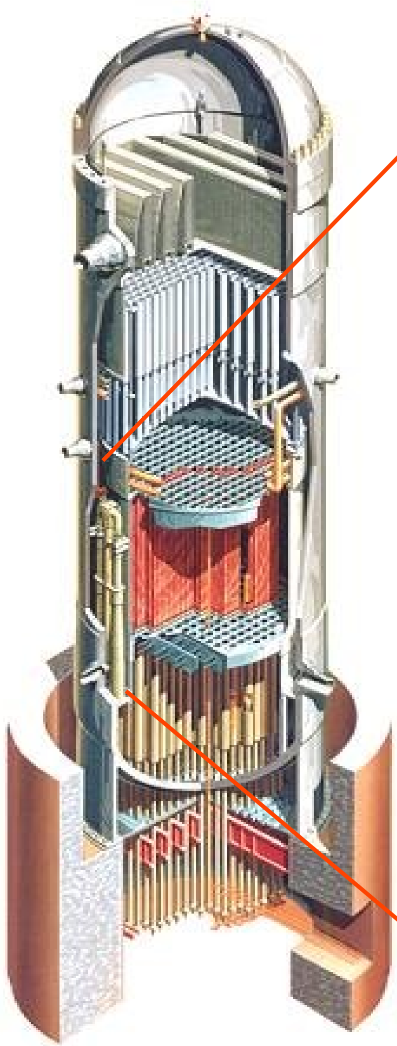


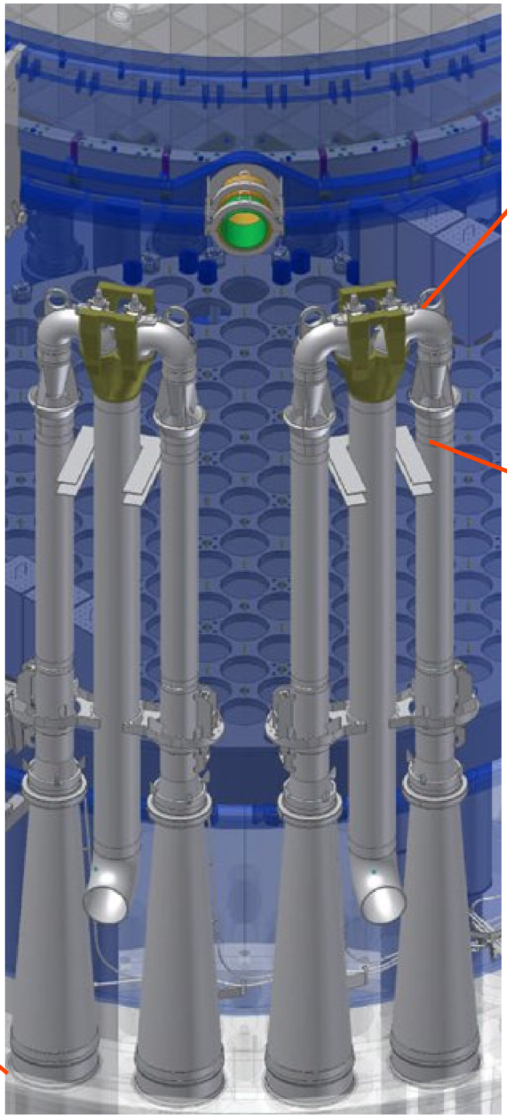
ABWR Power Cycle

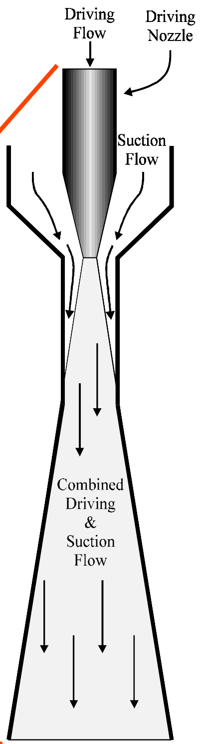


BWR Major
Internal Components

BWR Jet Pump

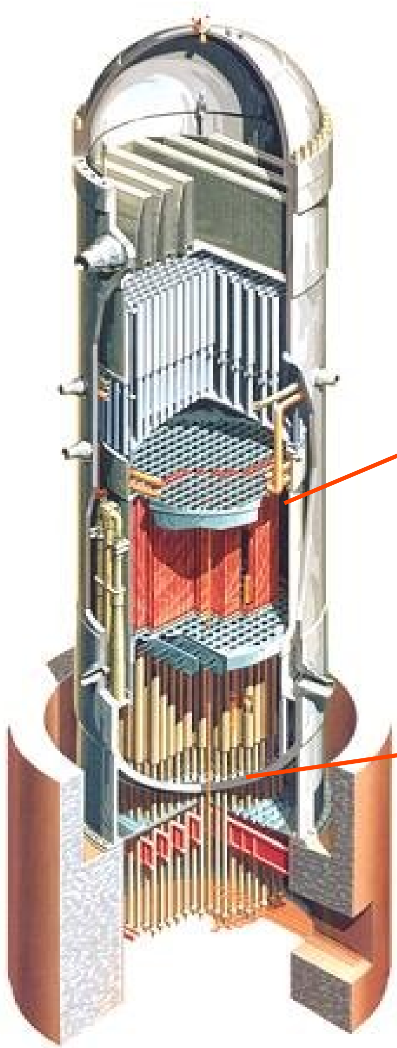




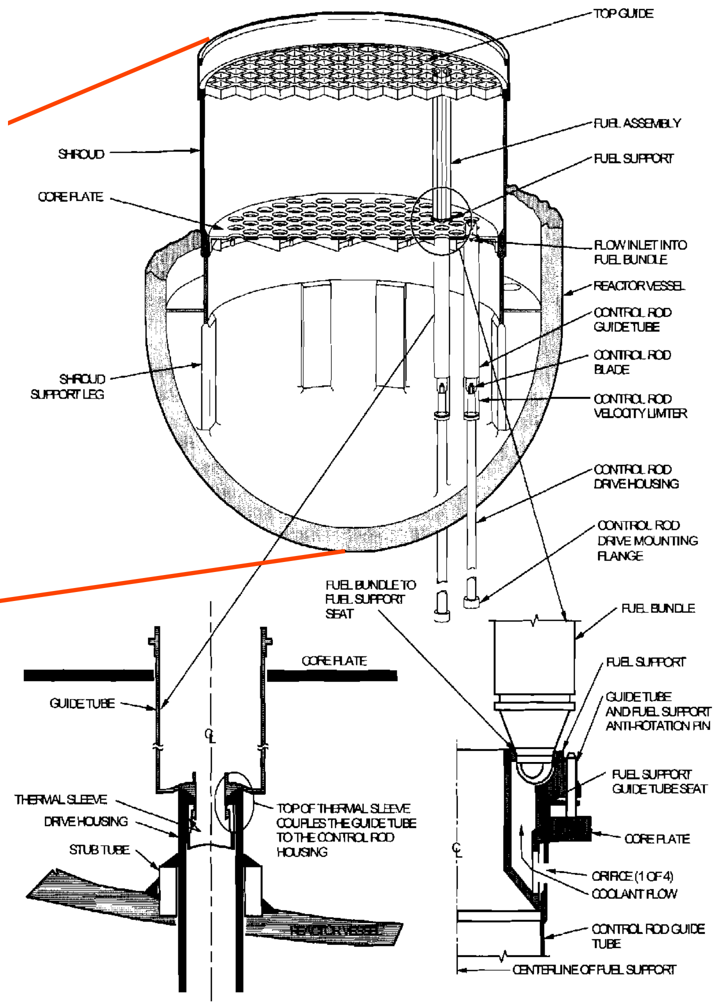


- **Provide core flow to control reactor power which yields higher power level without increasing the Rx size**
- **Provide part of the boundary required to maintain 2/3 core height following a recirculation line break event**

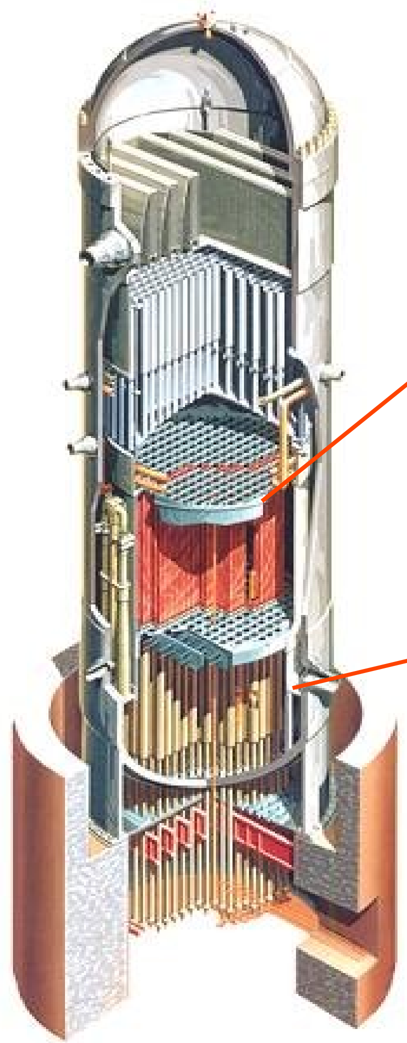
Lower Plenum

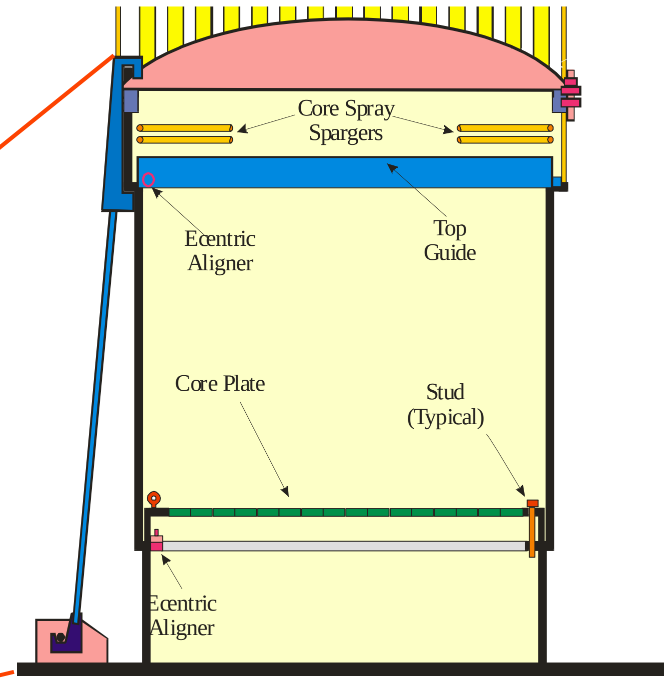


- CRD Guide Tubes
- CRBs
- CRD housings
- Stub Tubes
- In-core Housings
- Guide Tubes
- Flux monitor dry tubes



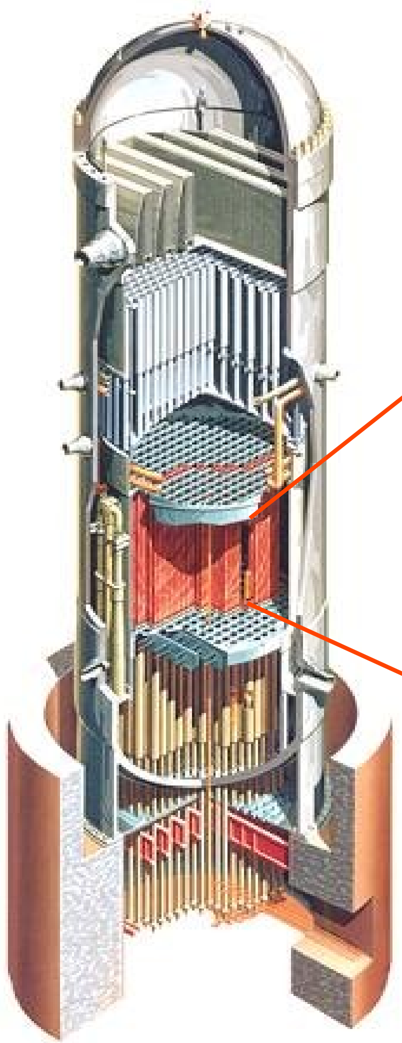
BWR Core Shroud

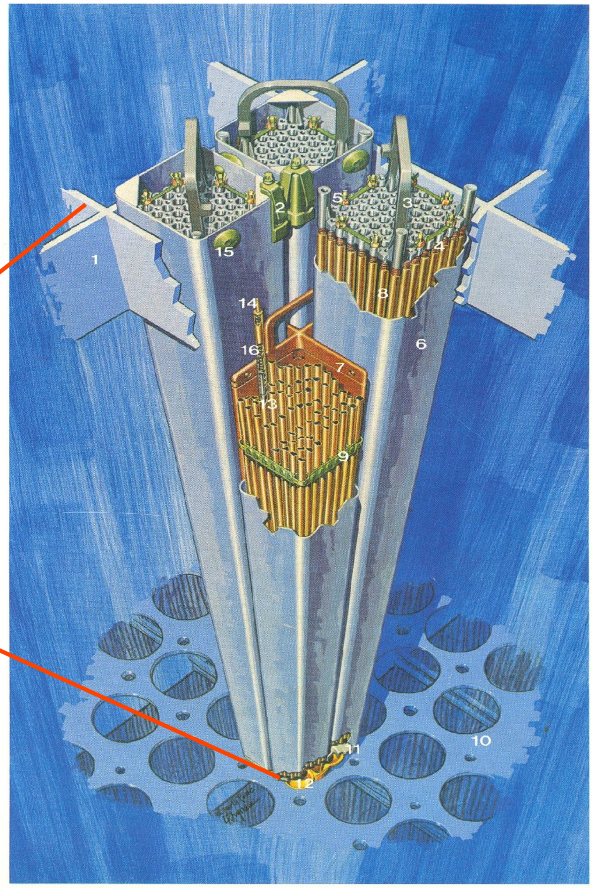


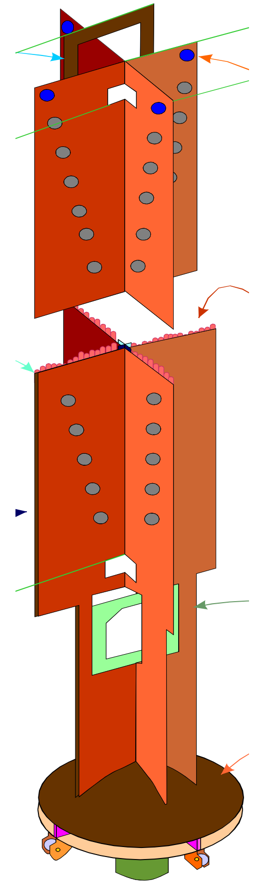


- Stainless Steel Cylinder
- Surrounds the Core
  - Separates upward flow through the core from downward flow in the downcomer annulus
  - Provides a 2/3 core height floodable volume

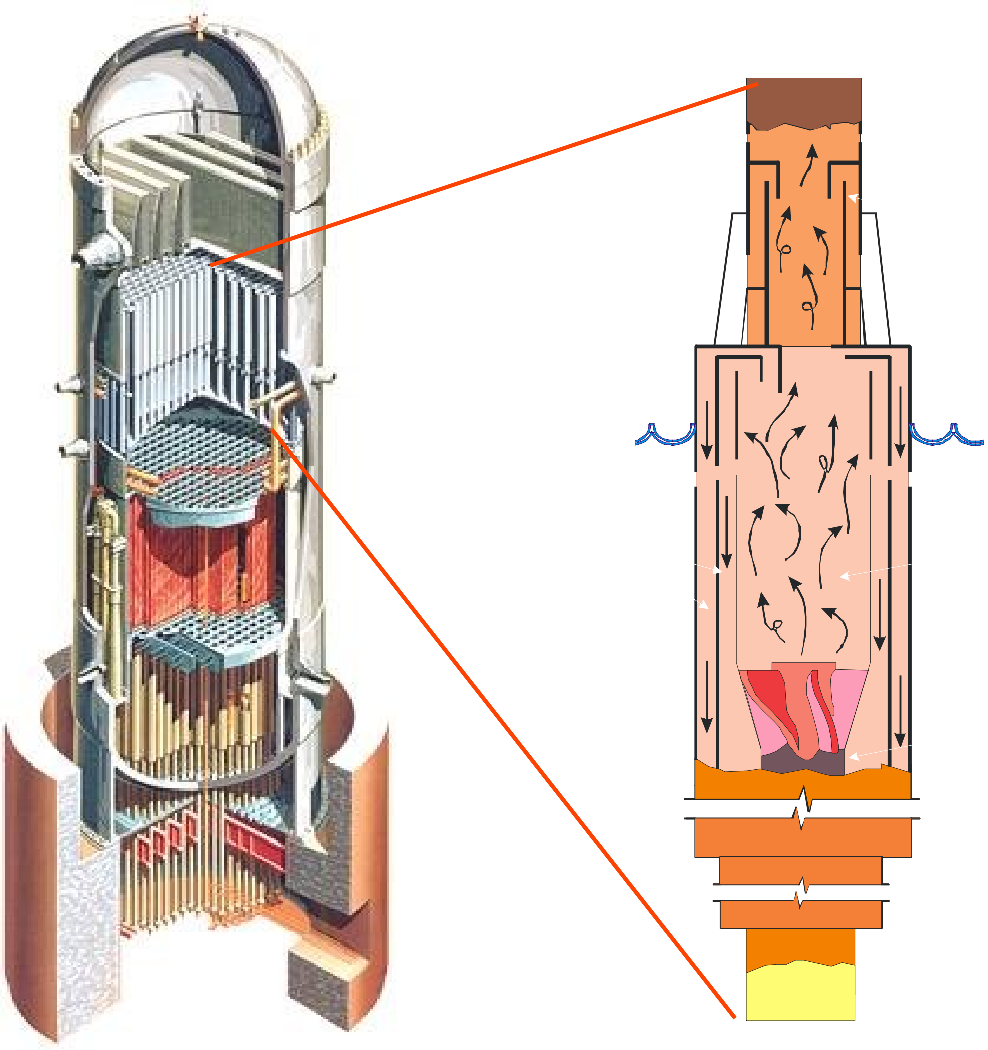
Fuel Assembly & Control Blade





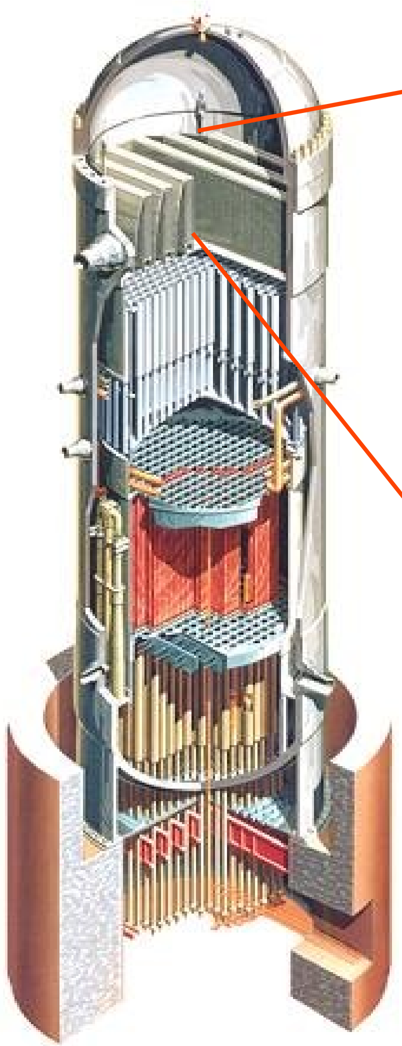


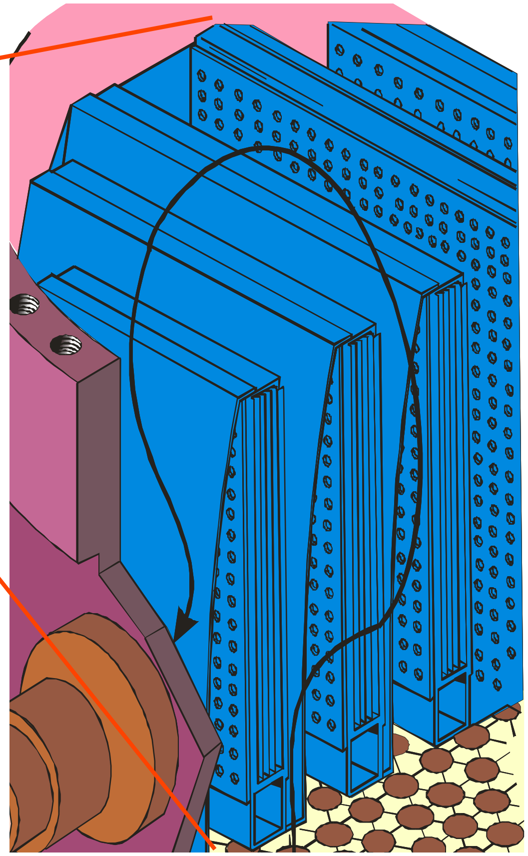
Steam Separator



- Turning vanes impart rotation to the steam/water mixture causing the liquid to be thrown to the outside
- 163 standpipes

Steam Dryer

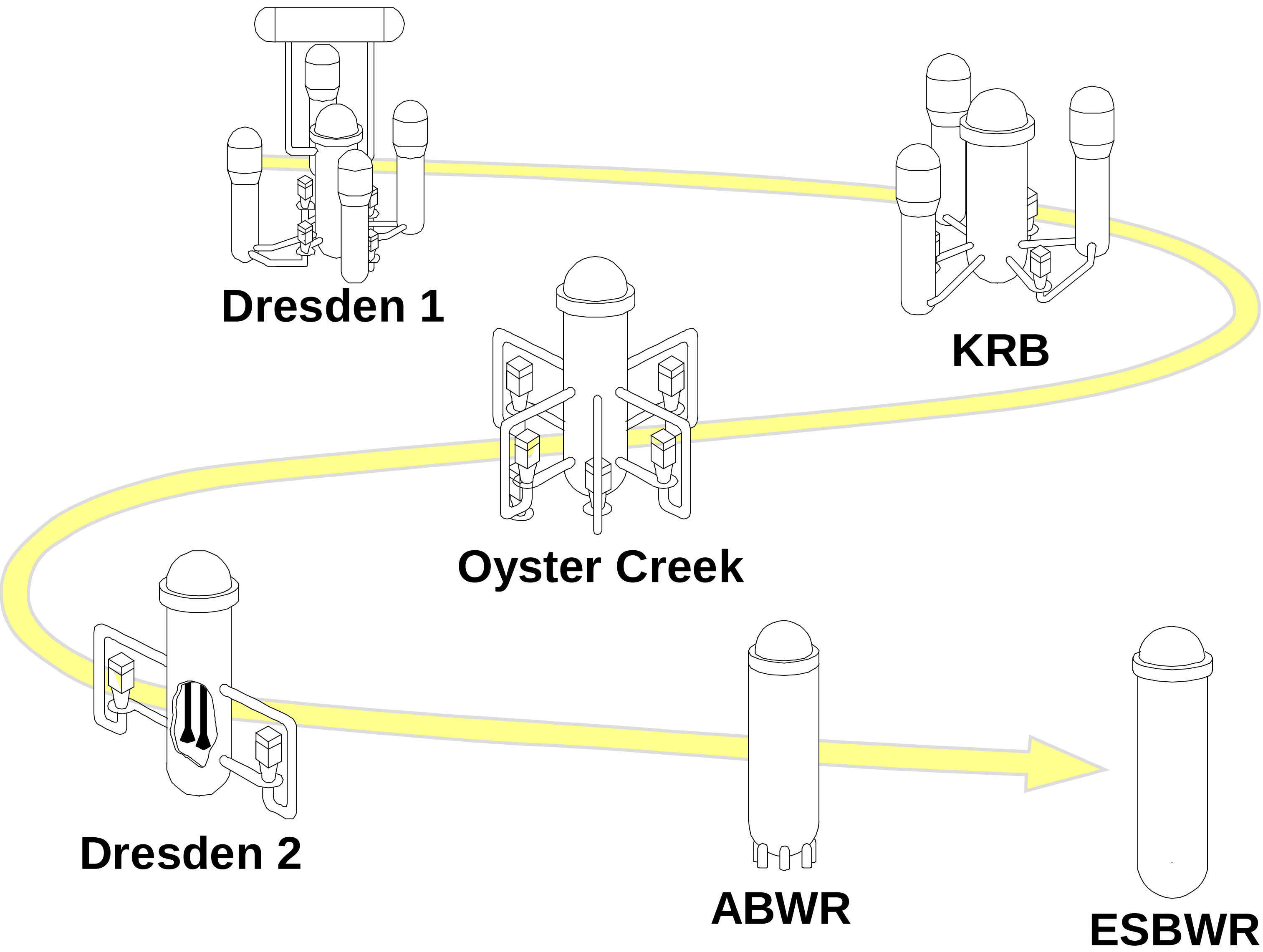




- Provides $Q_{steam\ dryer}$ = 99.9% to the Main Turbine
- Wet steam is forced horizontally through dryer panels
  - Forced to make a series of rapid changes in direction
  - Moisture is thrown to the outside
- Initial power uprate plants experiences FIV – minimized by design improvements

BWR Evolution

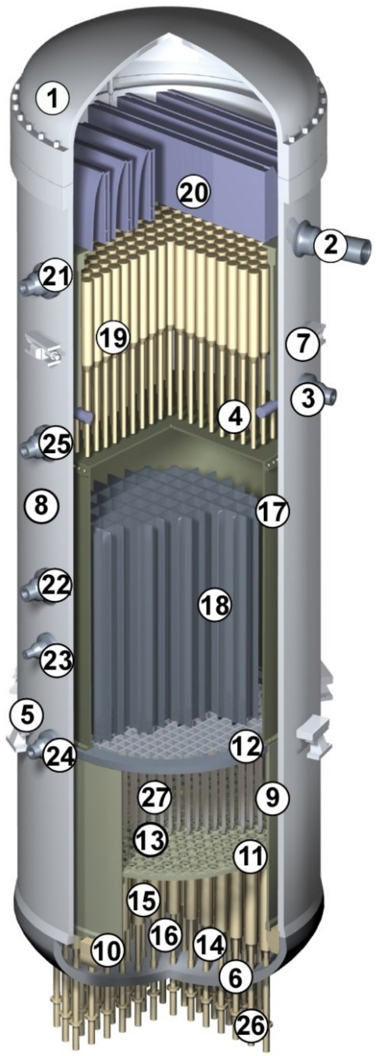
BWR Reactor Evolution



Operating Parameters for Selected BWRs

Parameter	BWR/4 (Browns Ferry 3)	BWR/6 (Grand Gulf 1)	ABWR	ESBWR
Power (MWt / MWe)	3293/1098	3900/1360	3926/1350	4500/1590
Vessel height / diameter (m)	21.9/6.4	21.8/6.4	21.1/7.1	27.6/7.1
Fuel Bundles (number)	764	800	872	1132
Active Fuel height (m)	3.7	3.7	3.7	3.0
Power density (kW/l)	50	54.2	51	54
Recirculation pumps	2 (large)	2 (large)	10	zero
Number of CRDs / type	185/LP	193/LP	205/FM	269/FM
Safety system pumps	9	9	18	zero
Safety Diesel Generator	2	3	3	zero
Core damage freq./yr	1E-5	1E-6	1E-7	1E-8
Safety Bldg Vol (m^3/MWe)	120	170	180	135

ESBWR Reactor Pressure Vessel

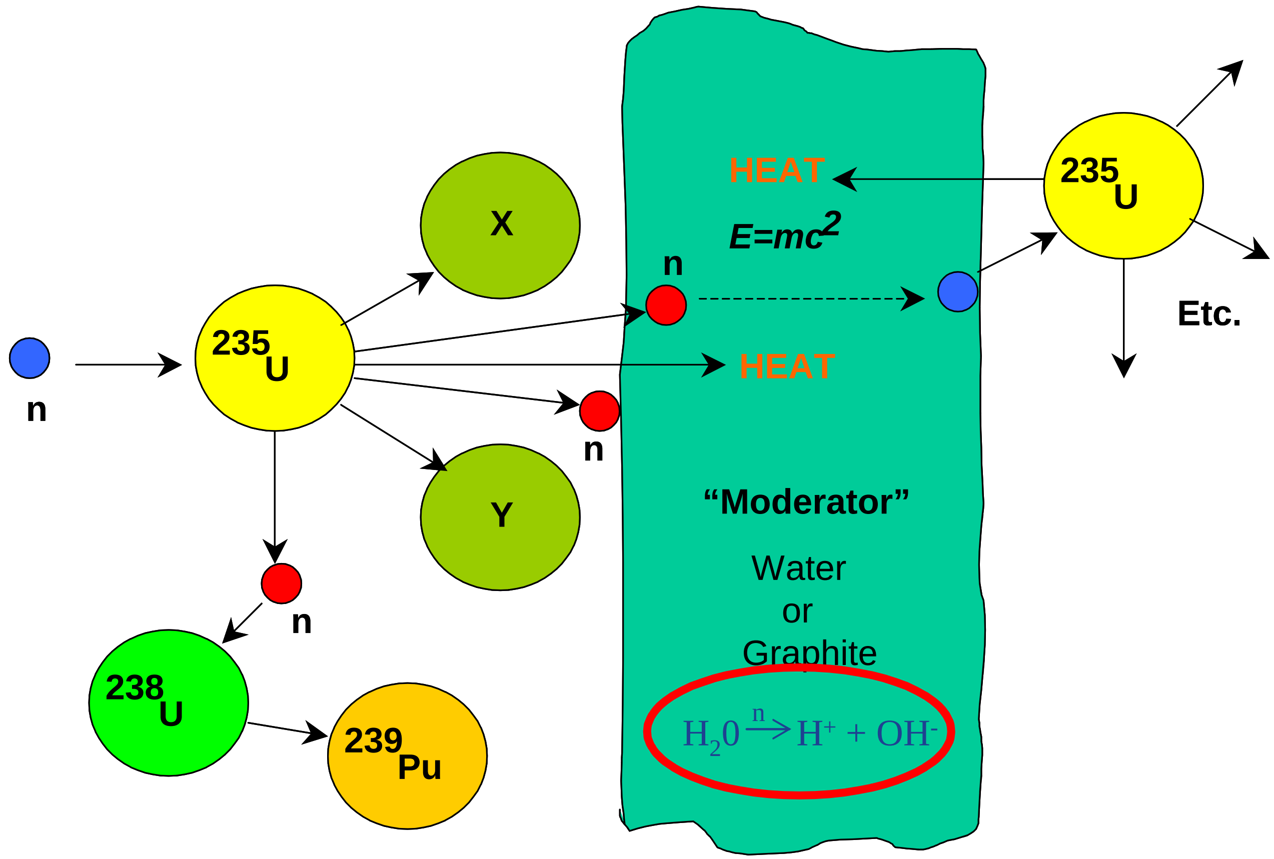


ESBWR

1. Vessel Flange and closure head
2. Steam outlet flow restrictor
3. Feedwater nozzle
4. Feedwater sparger
5. Vessel support
6. Vessel bottom head
7. Stabilizer
8. Forged shell rings
9. Core shroud
10. Shroud support brackets
11. Core plate
12. Top guide
13. Fuel supports
14. Control rod drive housings
15 Control rod guide tubes
16. In-core housing
17. Chimney
18. Chimney partitions
19. Steam separator assembly
20. Steam dryer assembly
21. DPV/IC outlet
22. IC return
23. GDCS inlet
24. GDCS equalizing line inlet
25. RWCU/SDC outlet
26. Control rod drives
27. Fuel and control rods

Stress Corrosion Cracking in BWRs

“Nuclear Chain Reactions on One Slide”



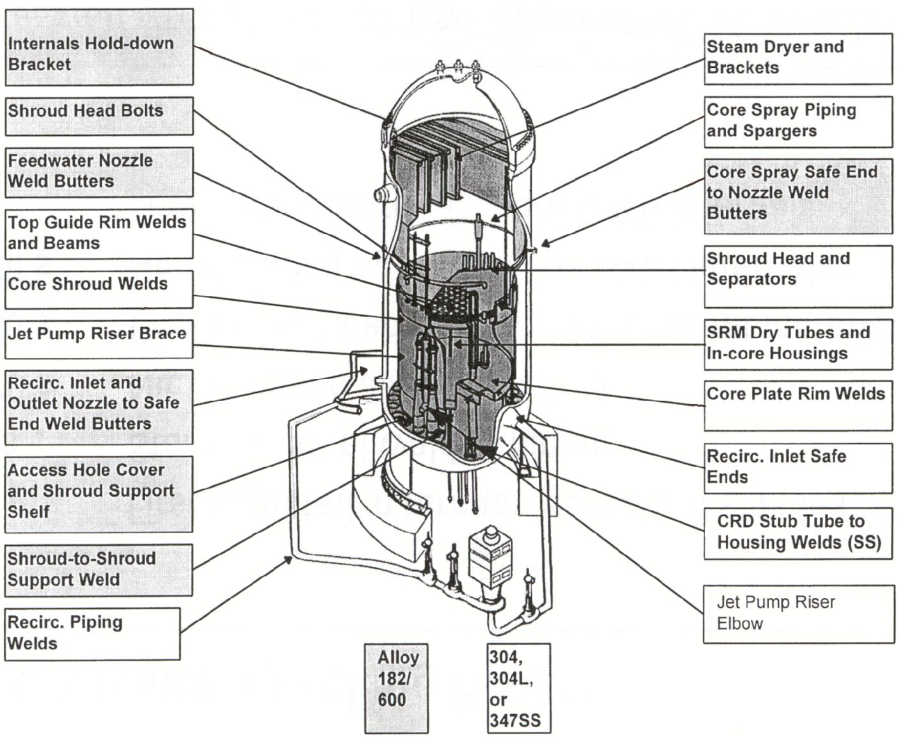
high energy neutron

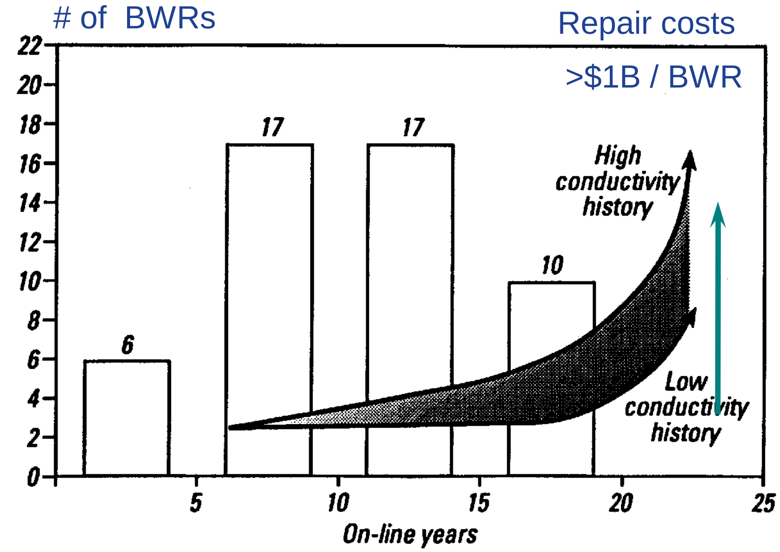
low energy neutron

X,Y Radioactive by-products

e.g. Kr, Cs, I, Ba, Th, Np

BWR Sens. SS Piping → Core Components





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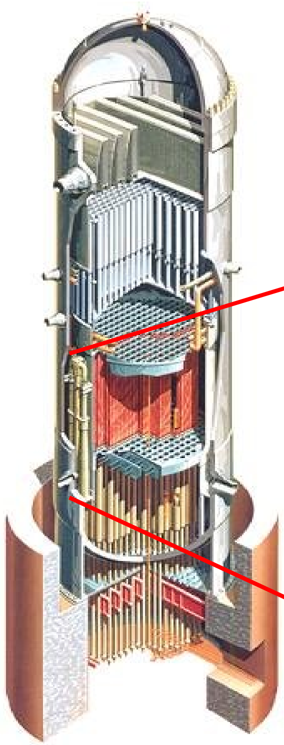
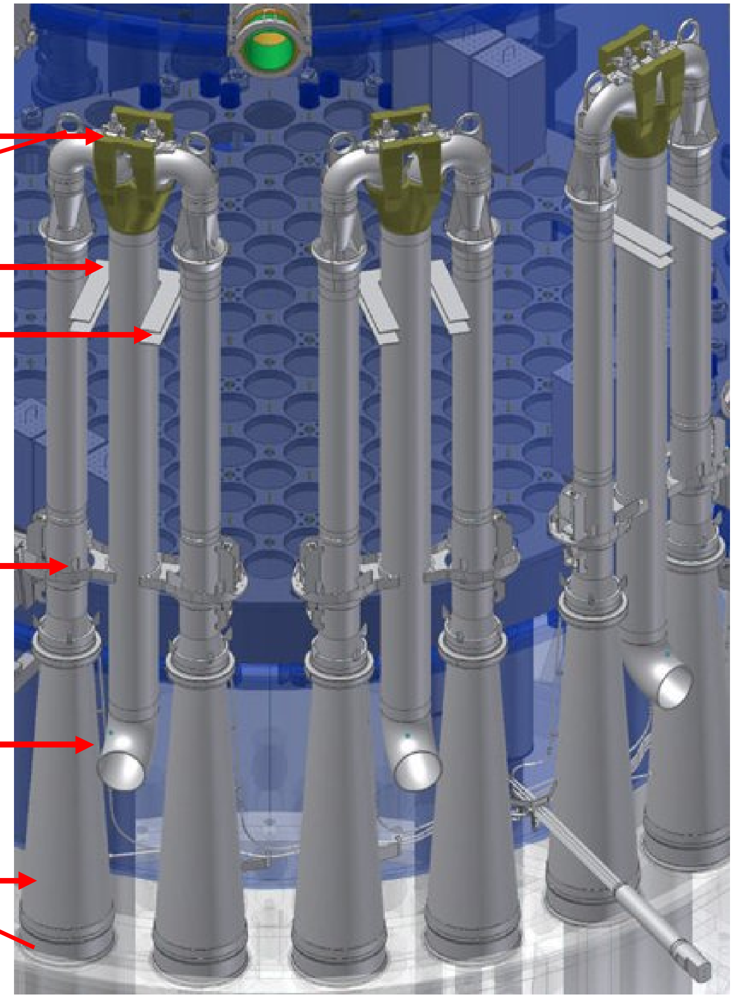
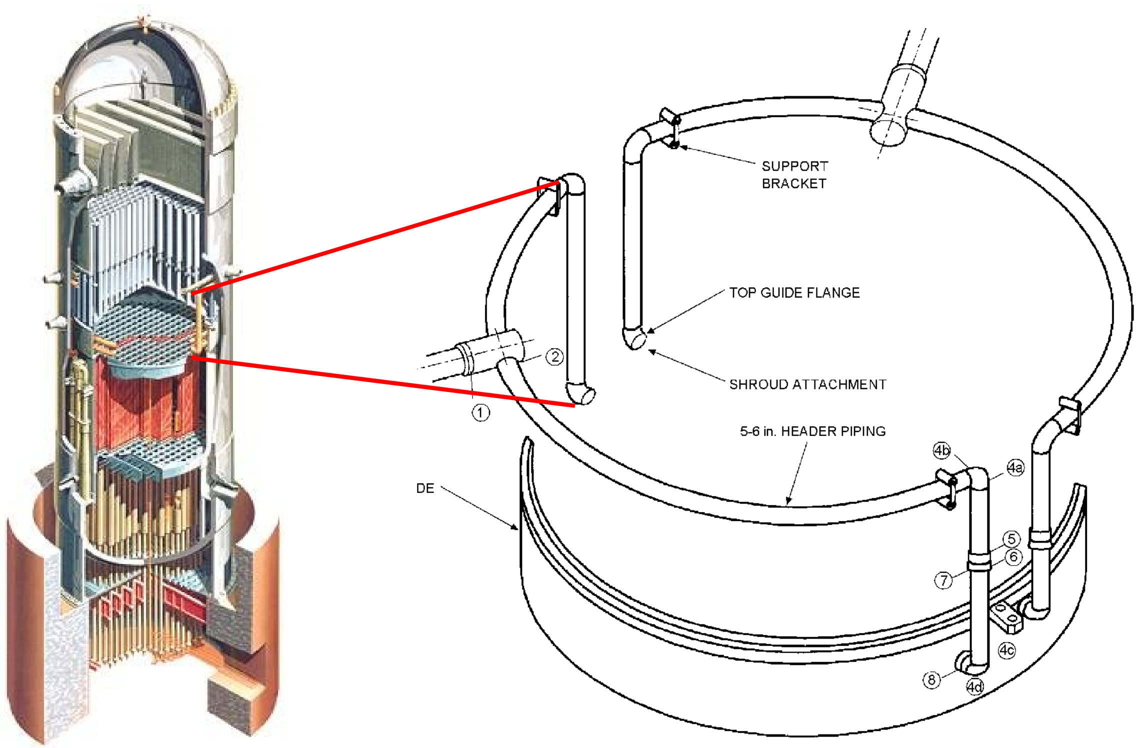
Cracking in Jet Pump Assembly

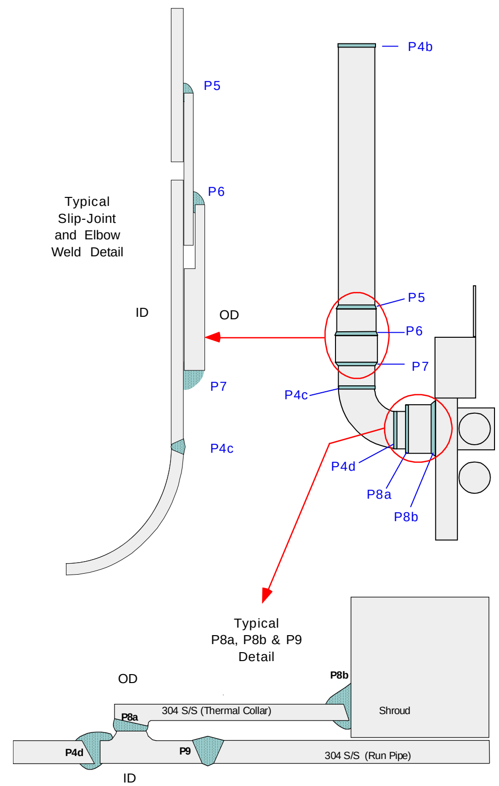




Cracking in Core Spray Piping

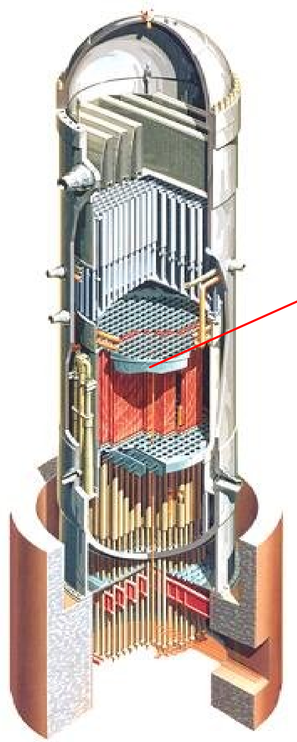
- Safety system contains many welds
  - Highly oxidizing environment
  - Not able to be protected with changes in water chemistry





Top Guide Cracking

- Very redundant structure
- Long term risk of IASCC after long radiation exposure



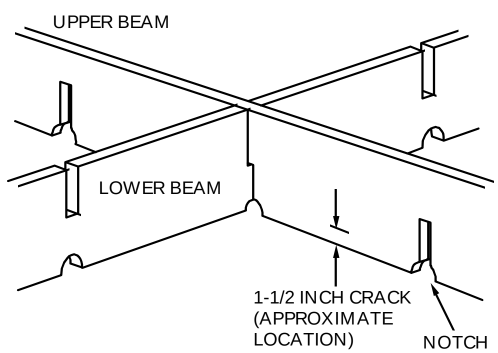
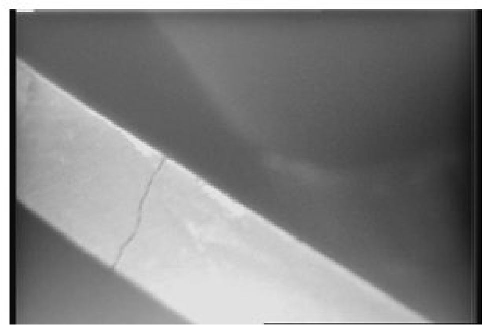
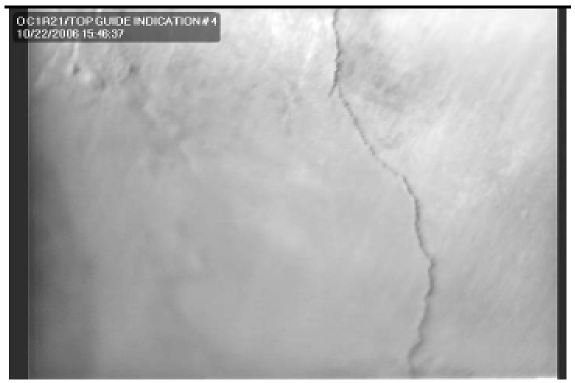
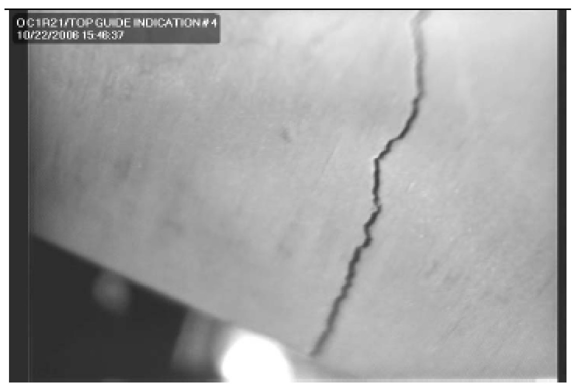


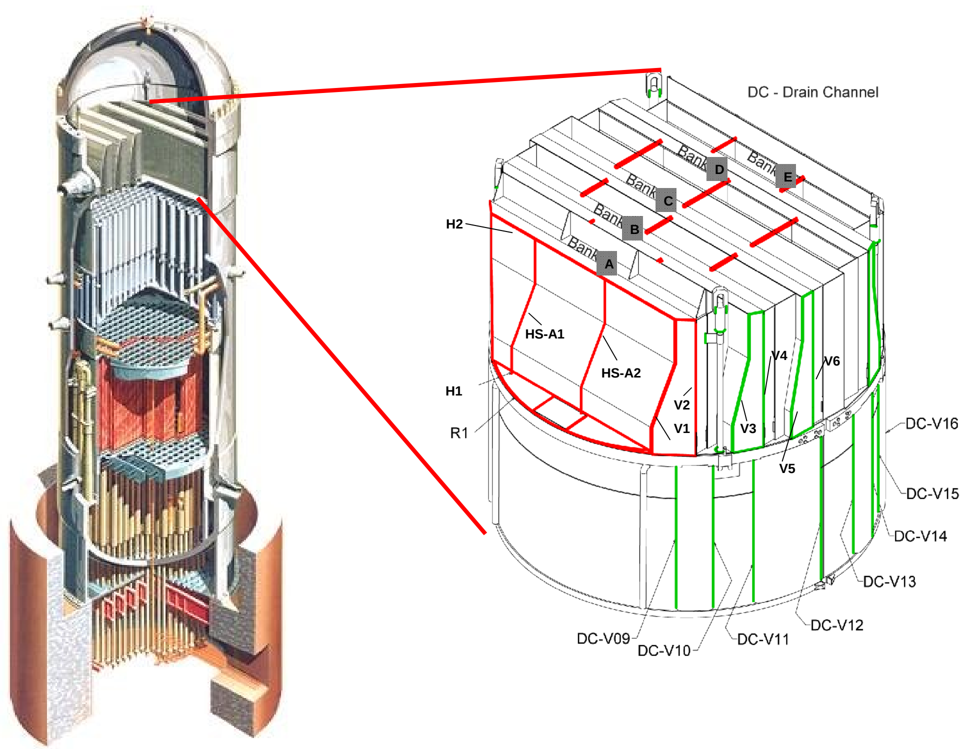
Figure 2-1.

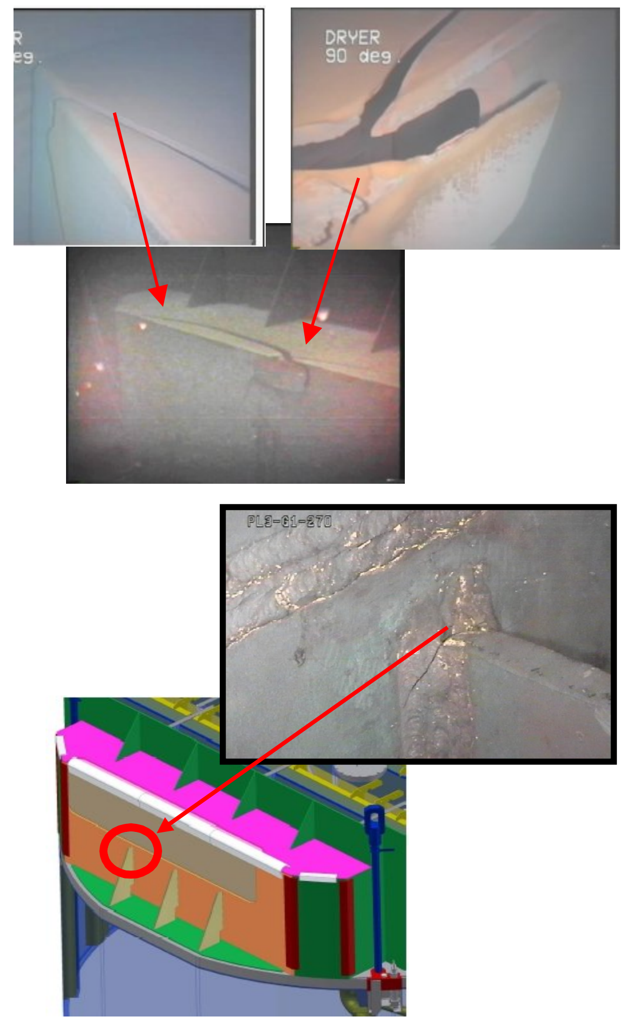






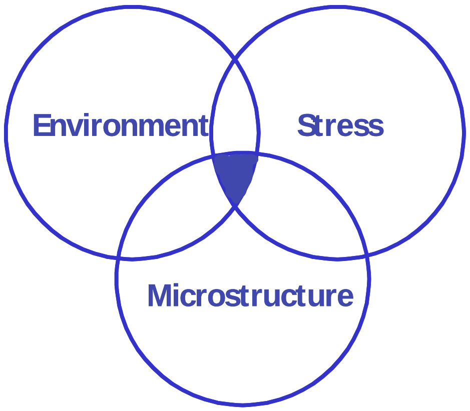
Steam Dryer Cracking

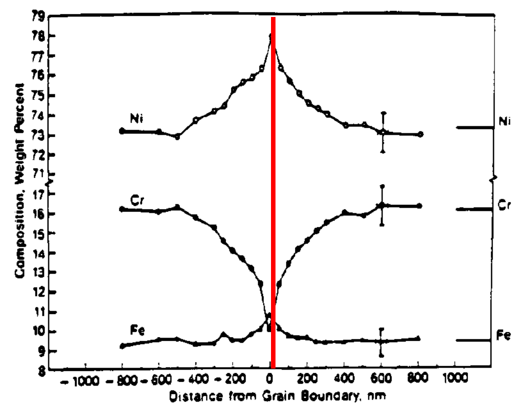




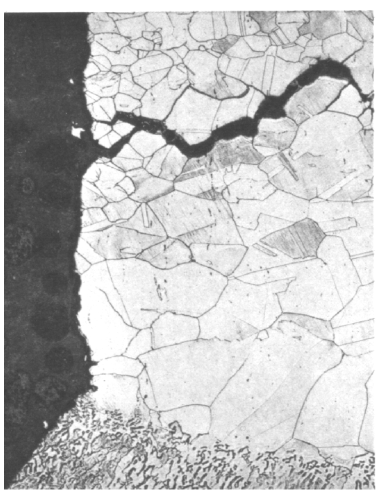
Significant fatigue/corrosion fatigue cracking found following power uprates

Stress Corrosion Cracking

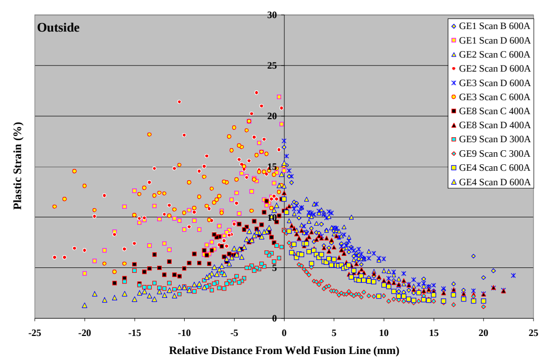




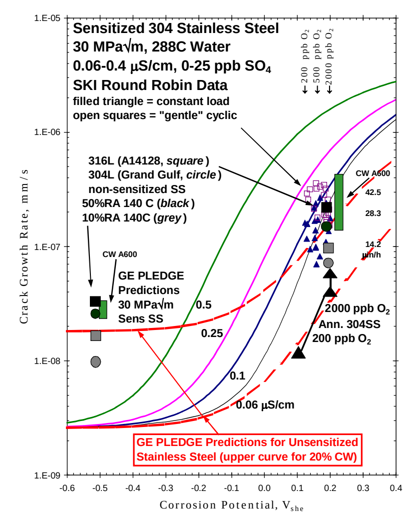
Cr depletion occurs during welding of stainless steels with high carbon levels



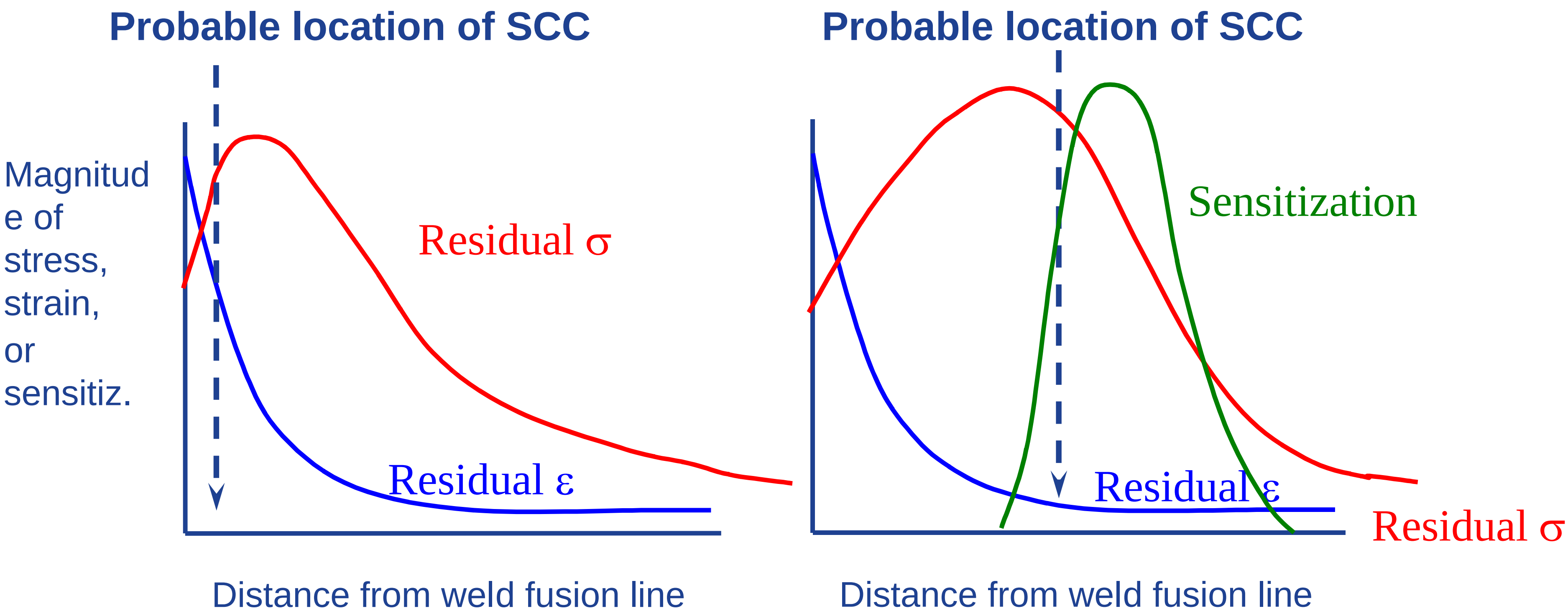
Weld



Plastic strain occurs during welding and leads to cracking in stainless steels with low carbon (L-grade SS)



Balancing Factors in Location of SCC



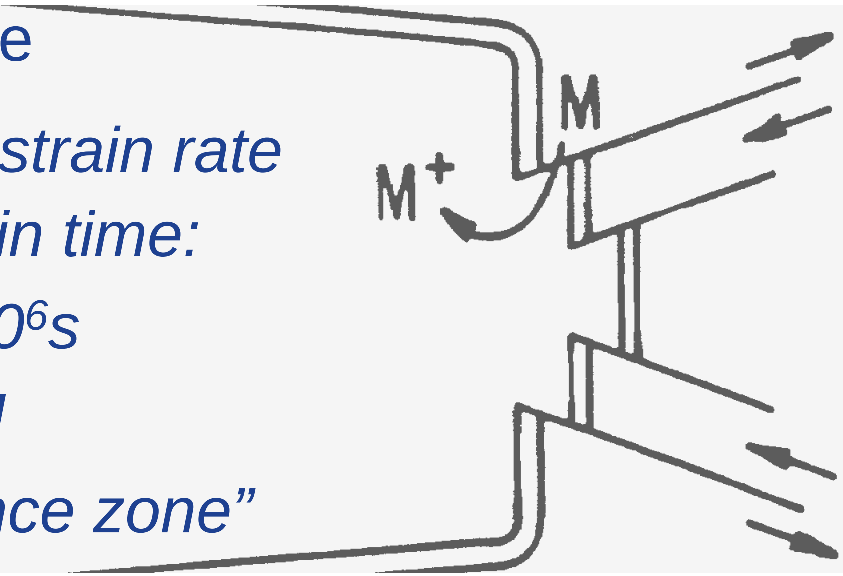
SCC = f (residual σ, residual ε, sensitization –
& ECP, water chemistry…)

Role of Deformation Kinetics in SCC

Deformation impinges on crack tip as large shear strains, readily producing oxide fracture

The crack growth rate – crack tip strain rate synergy is complex spatially & in time:

- *passivation can continue > 10^6s*
- *different slip planes activated*
- *many grains in "linked influence zone"*



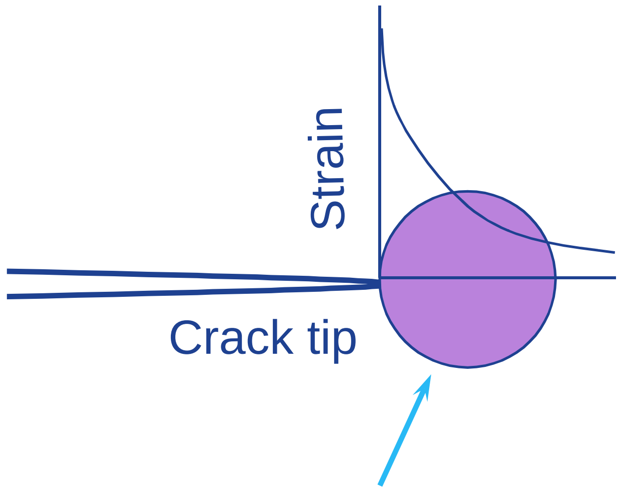
The same processes affect crack nucleation

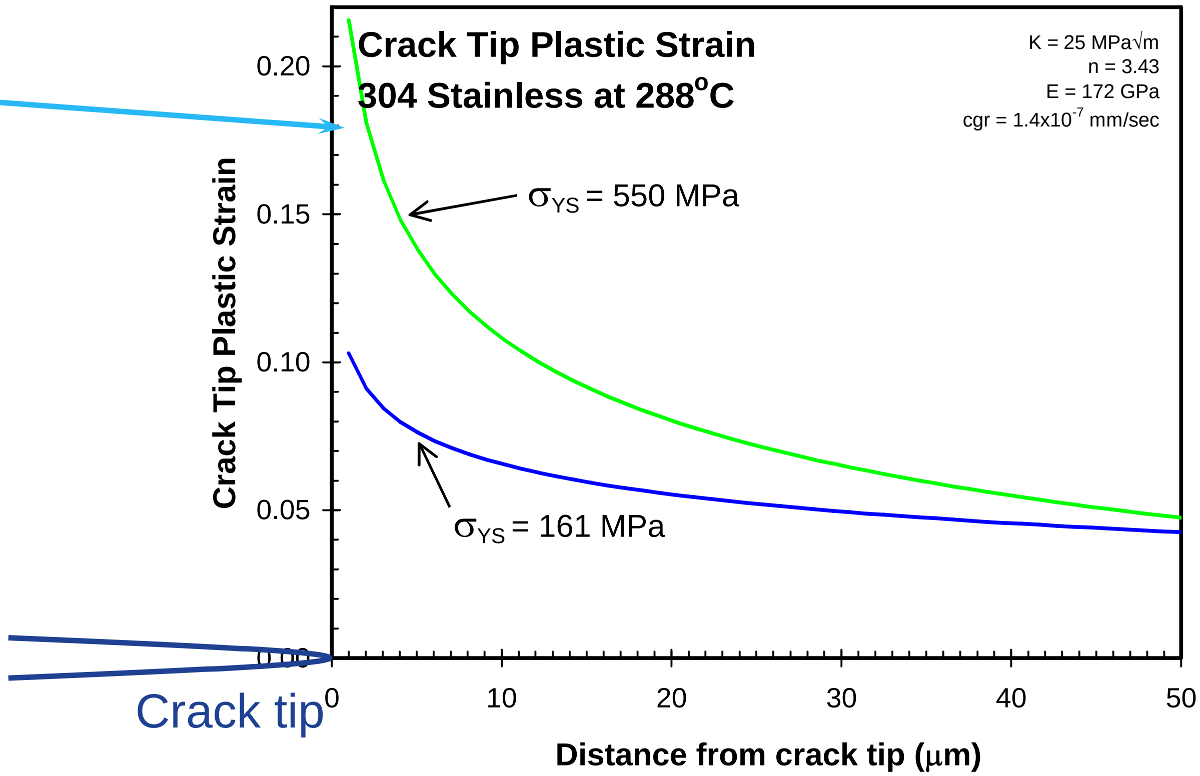
Localization of deformation on smooth surfaces plays a large role, esp. if no chemical (e.g., Cr) preference exists

Crack Tip Strain Rate

At constant load, crack tip strain rate occurs due to strain redistribution as the crack grows.

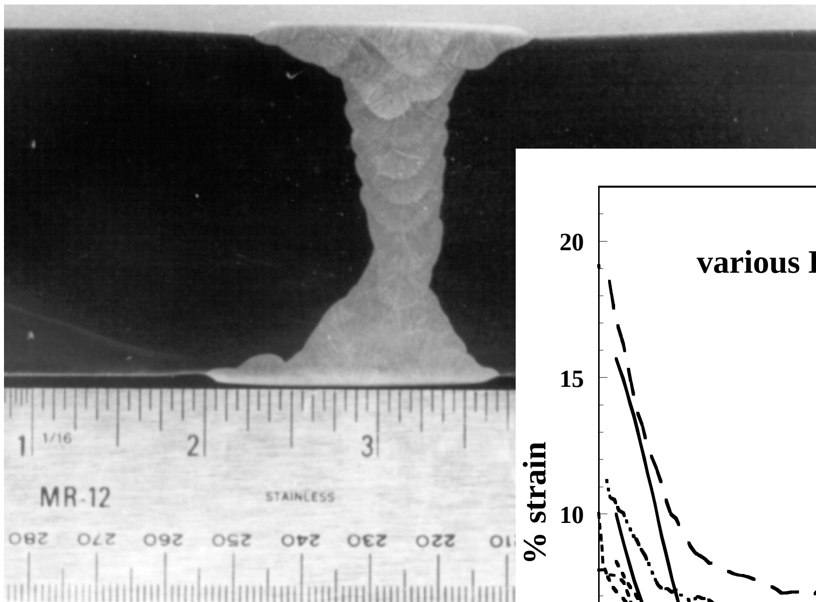
↑yield strength ↑dε/da

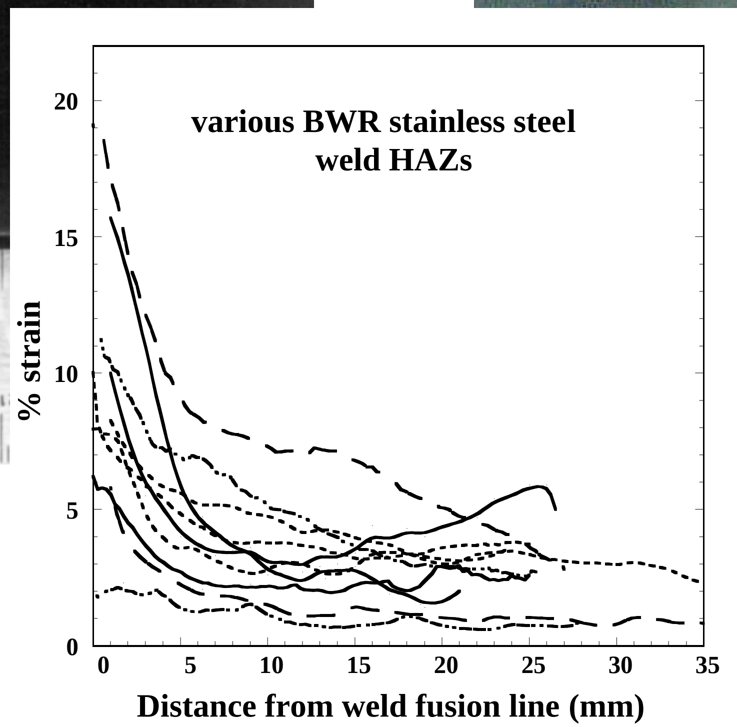


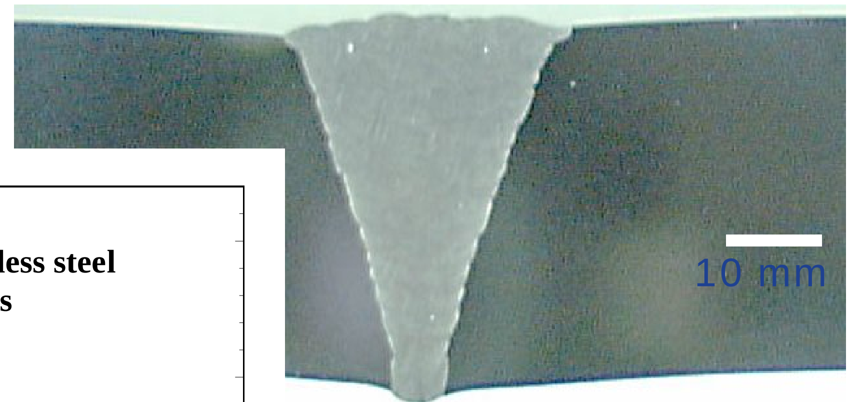


Conceptually, the zone of influence is the distance over which there is a direct influence on the crack tip strain rate

Plastic Strains at Welds







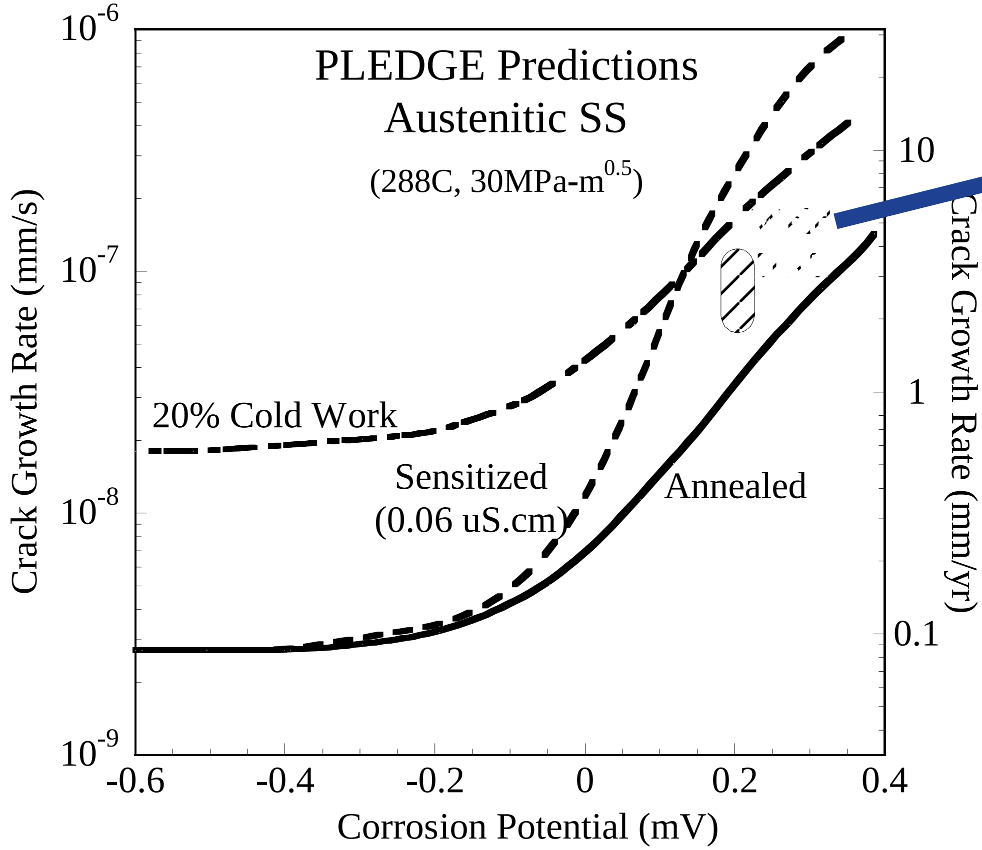
Typical Shroud & Pipe Welds and Strain Levels in Heat Affected Zone (HAZ)

Residual Strain Discussion

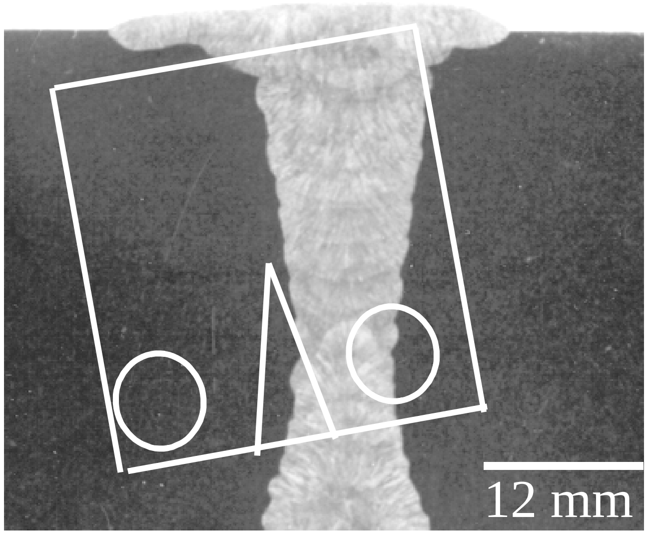
Residual strains result from shrinkage during welding

- Geometry / constraint believed to control magnitude of strain

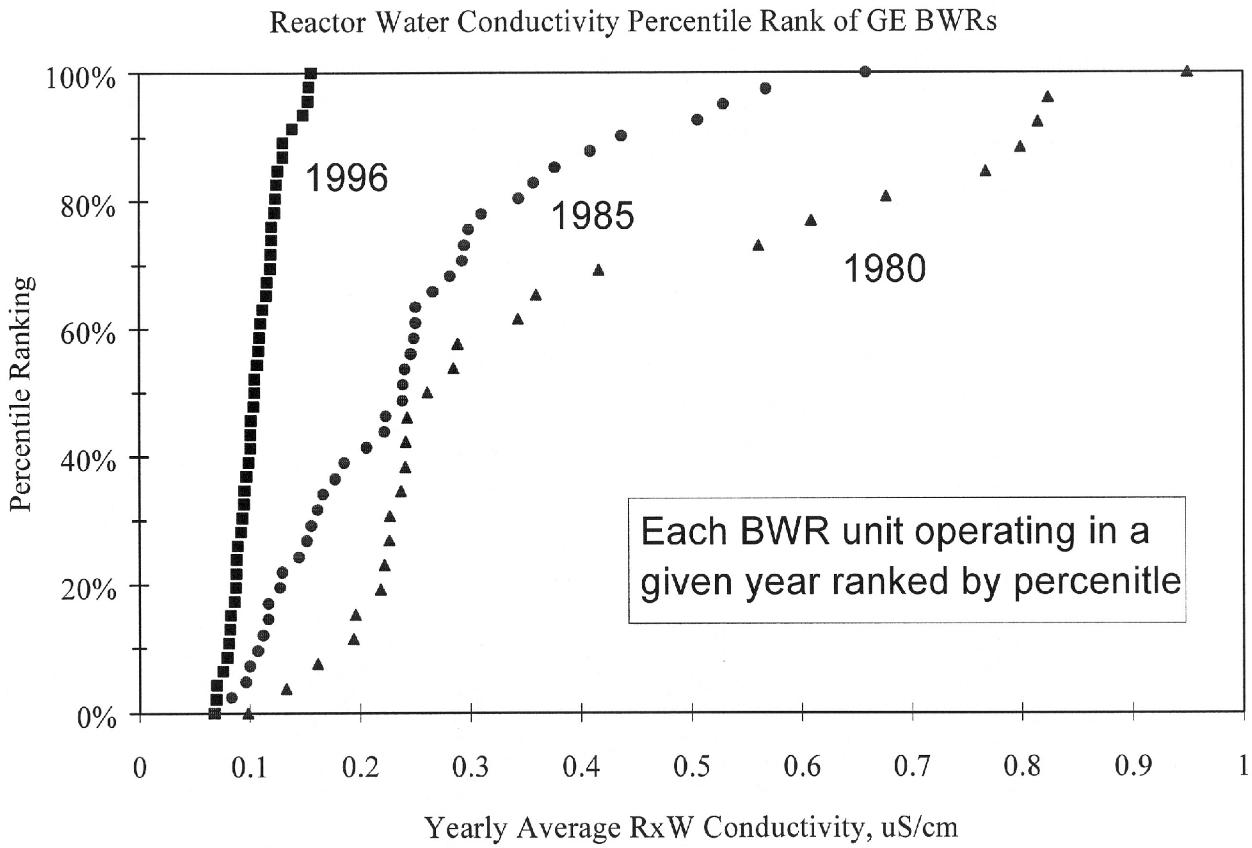
Deformation / cold work / residual strain promotes IGSCC



Interior locations of 304L (W0) & 316L (W1) 10 to 15% strain



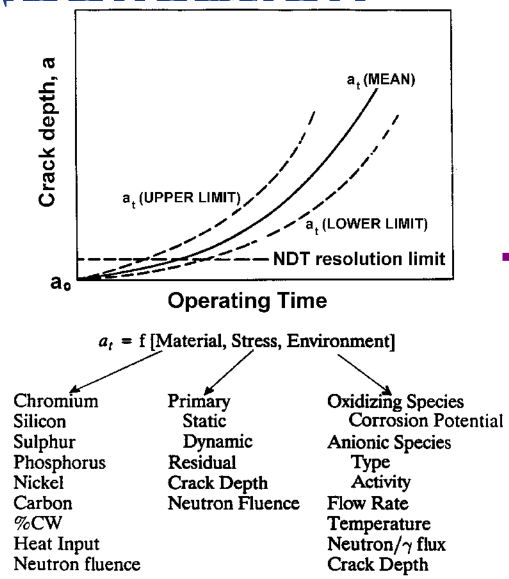
SCC Water Purity Mitigation Taken



Improved BWR water; 0.055 µS/cm = theoretical purity

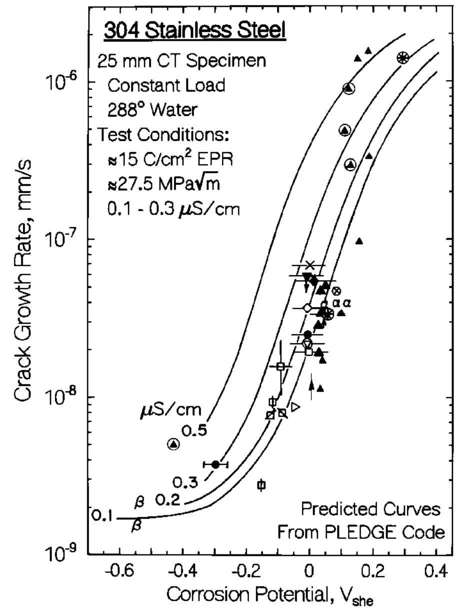
0.10 µS/cm = 10 ppb Cl^-; 0.9 µS/cm = 100 ppb Cl^-

Stress Corrosion Cracking Prediction & Application



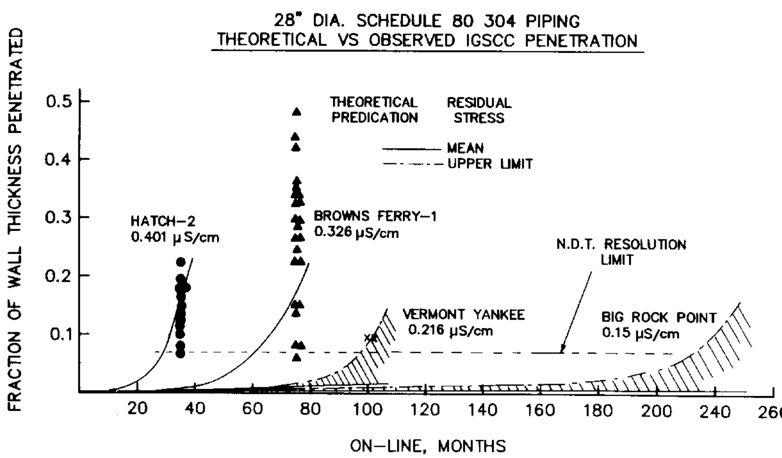
Complex phenomenon must be understood mechanistically as "crack tip system" processes

LAB

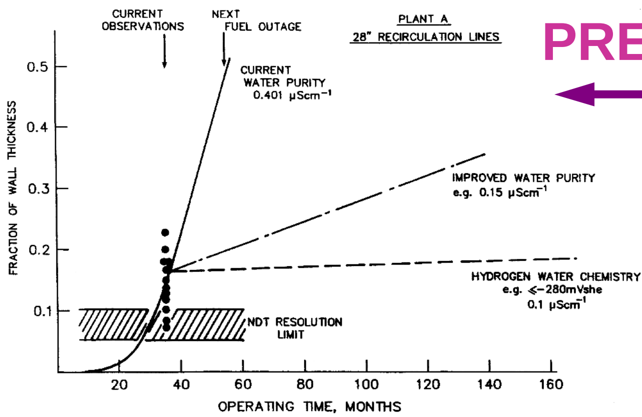


Lab understanding & data must be verified by plant data before use in BWR prediction

PLANT



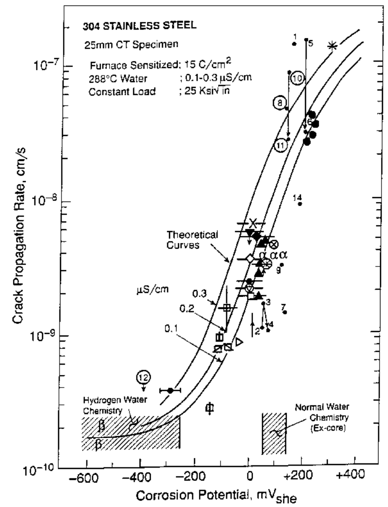
PREDICTION



Insights yield novel technology like NobleChem

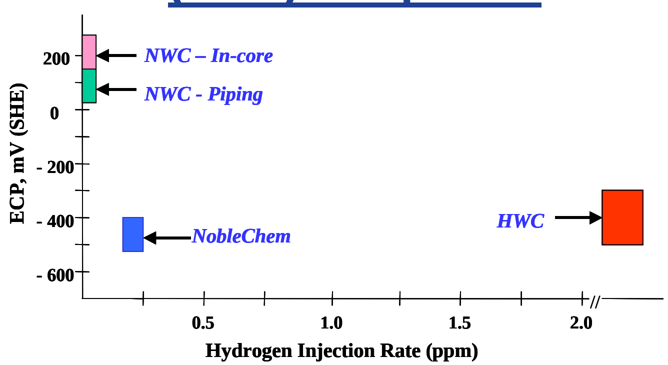
SCC, ECP and NobleChem™ Basics

Crack Growth Response

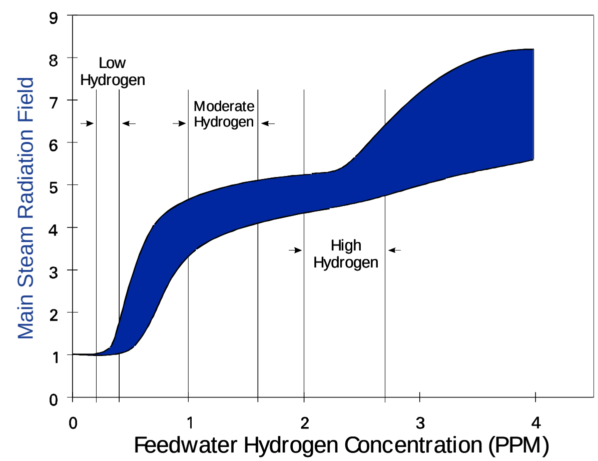


- High crack growth rates at high corrosion potential (ECP)
- ECP is a dominant variable effecting SCC response

Electro Chemical Potential (ECP) Response

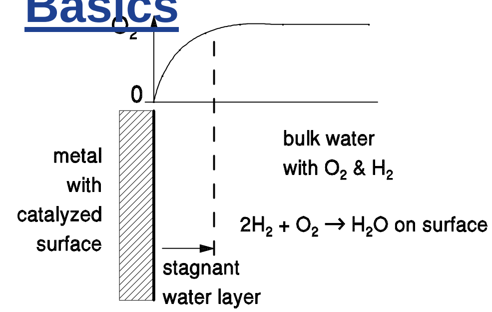


Radiation Field Response



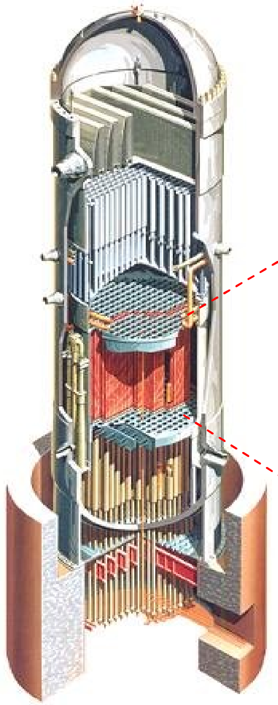
- Hydrogen injection results in an increase in main steam line radiation fields

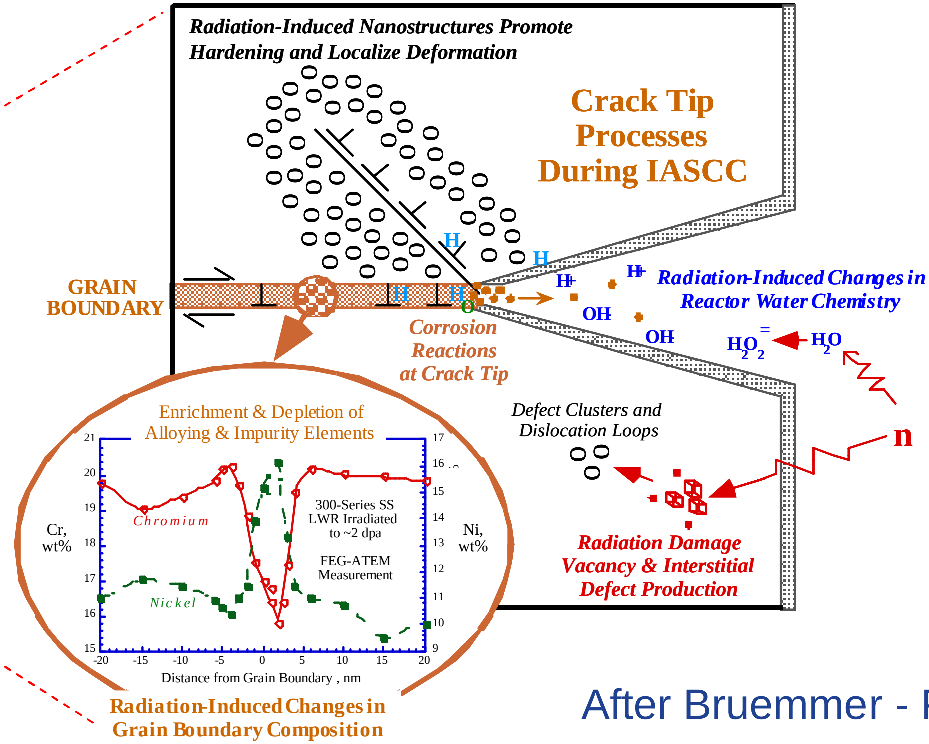
NobleChem™ Basics



- With excess H2, O2 is consumed & its level at the surface is zero
- $H_2 + O_2$ reaction is catalyzed with NobleChem particles
- Hydrogen added is more effective – lower radiation fields

Irradiation-Assisted Stress Corrosion Cracking



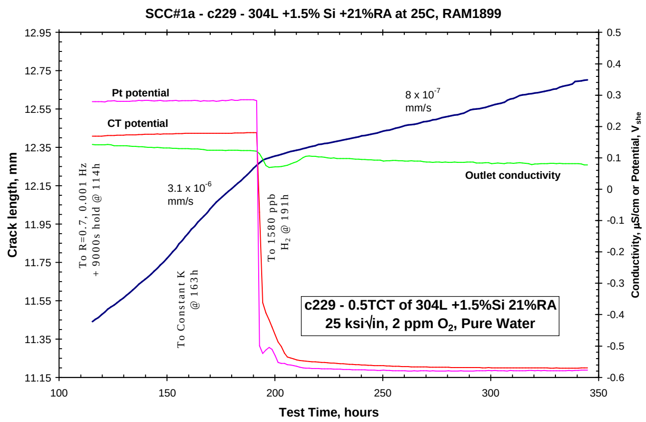


After Bruemmer - PNNL

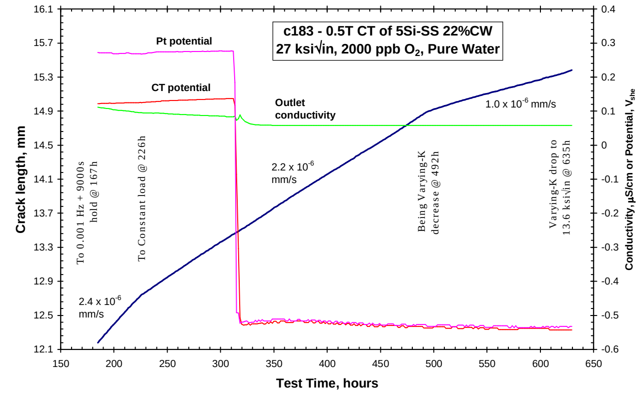
- Cr depletion occurs at grain boundary – not an issue at low corrosion potentials
- Si enrichment occurs –soluble in high temperature water
- Irradiation hardening occurs as a result of neutron damage
- Irradiation creep helps to decrease residual welding stress
- Understanding strain distribution at crack tip will enhance basic model development

Irradiation-Assisted Stress Corrosion Cracking

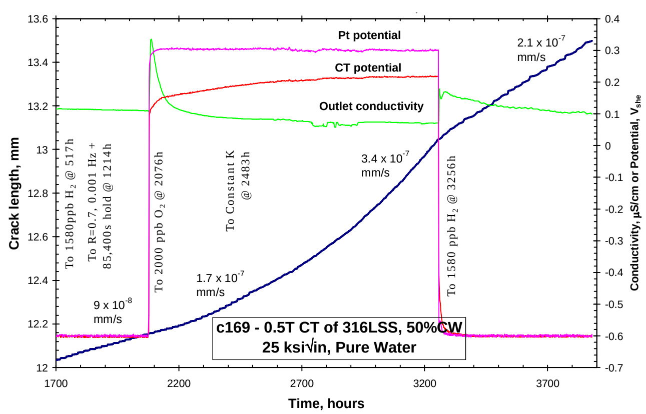
Type 304 + 1.5% Si



Type 304 + 5% Si



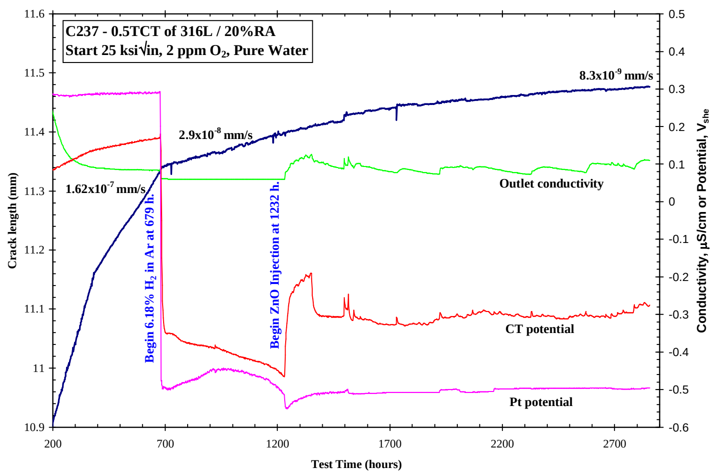
High Strength Type 304



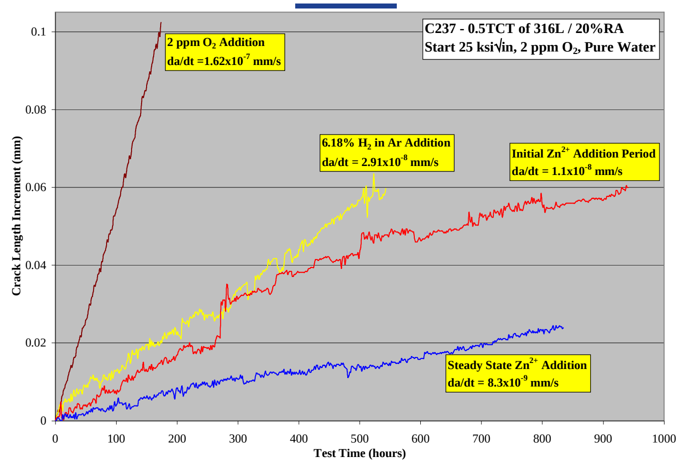
- Increased Si results in high crack growth rates at low potentials in stainless steels
- Increased yield strength (cold rolling) results in high crack growth rates at low potentials in stainless steels
- NobleChem will not effectively mitigate cracking in highly irradiated materials

Irradiation-Assisted Stress Corrosion Cracking

NobleChem + 20 ppb Zn^{2+}



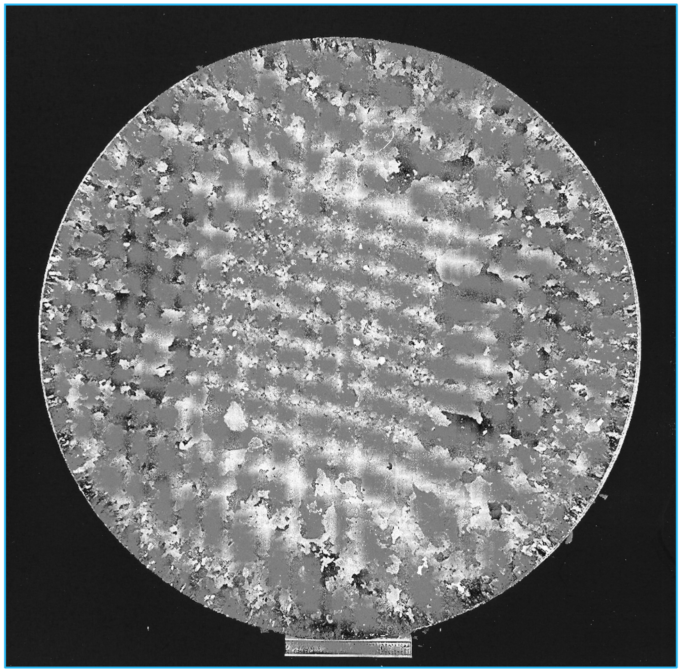
Longer-term Effects of Zn on SCC



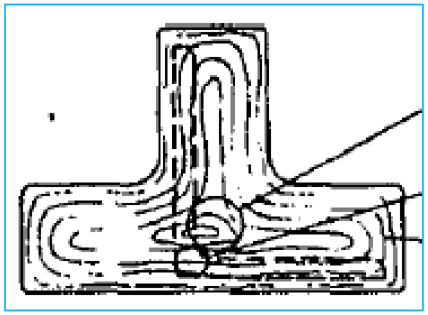
- **Injection of Zn^{+2} at low potentials may mitigate cracking in highly irradiated materials**
- **Future work will investigate the effect of Zn on Si containing alloys**
- **Zn is currently injected at low levels (5-7ppb) into reactor feed water for radiation field control**

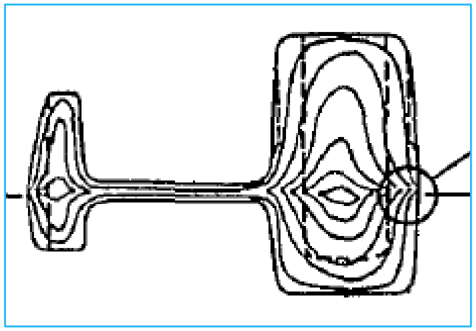
Material Processing Issues

Thermal Mechanical Processing



20” Diameter Starting Ingot

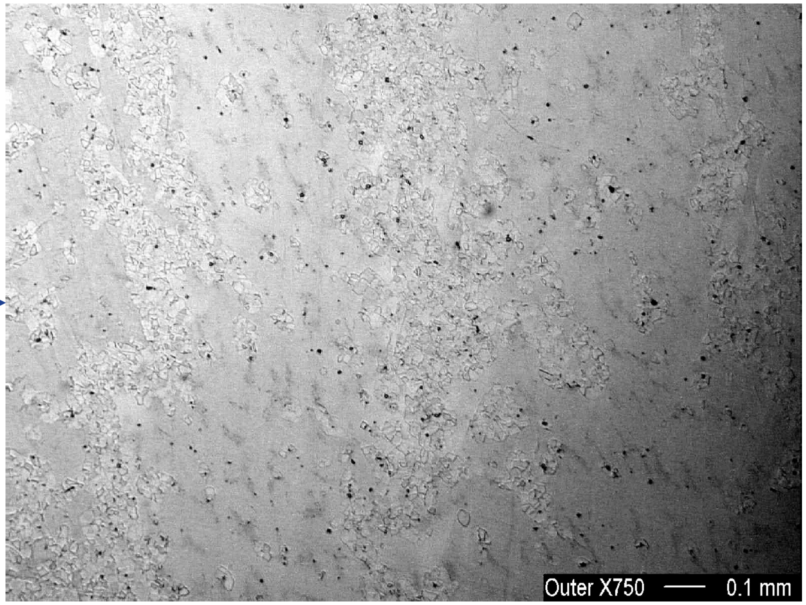


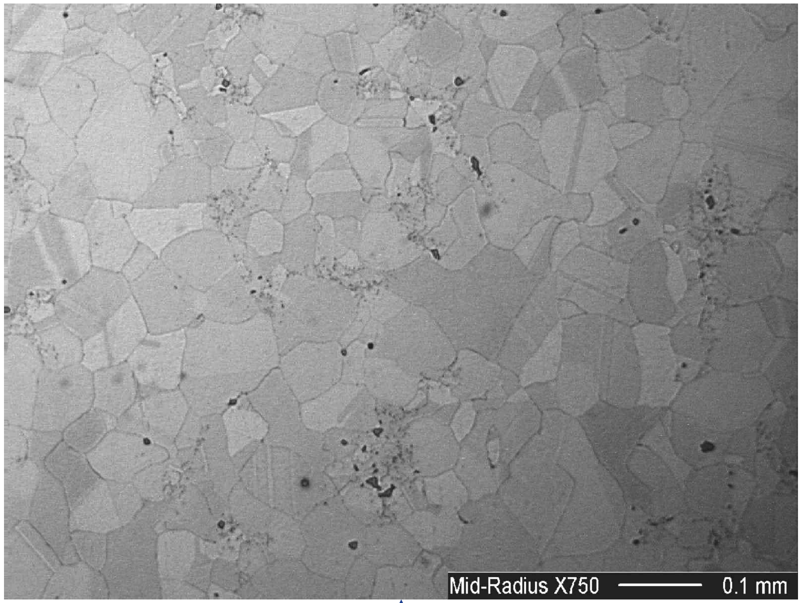


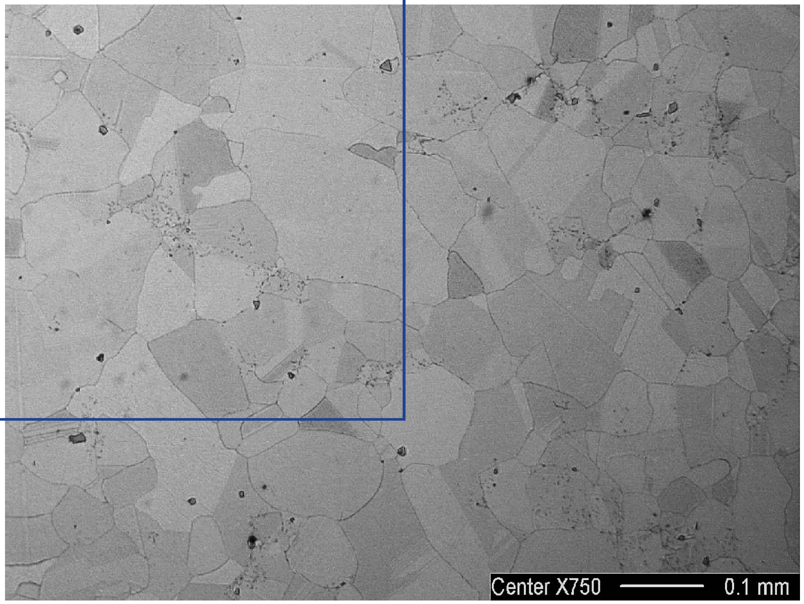
Highly Deformed Final Component

Carefully controlled thermal mechanical processing is needed to achieve uniform microstructures and mechanical properties

Unrecrystallized grains due to ingot conversion practice







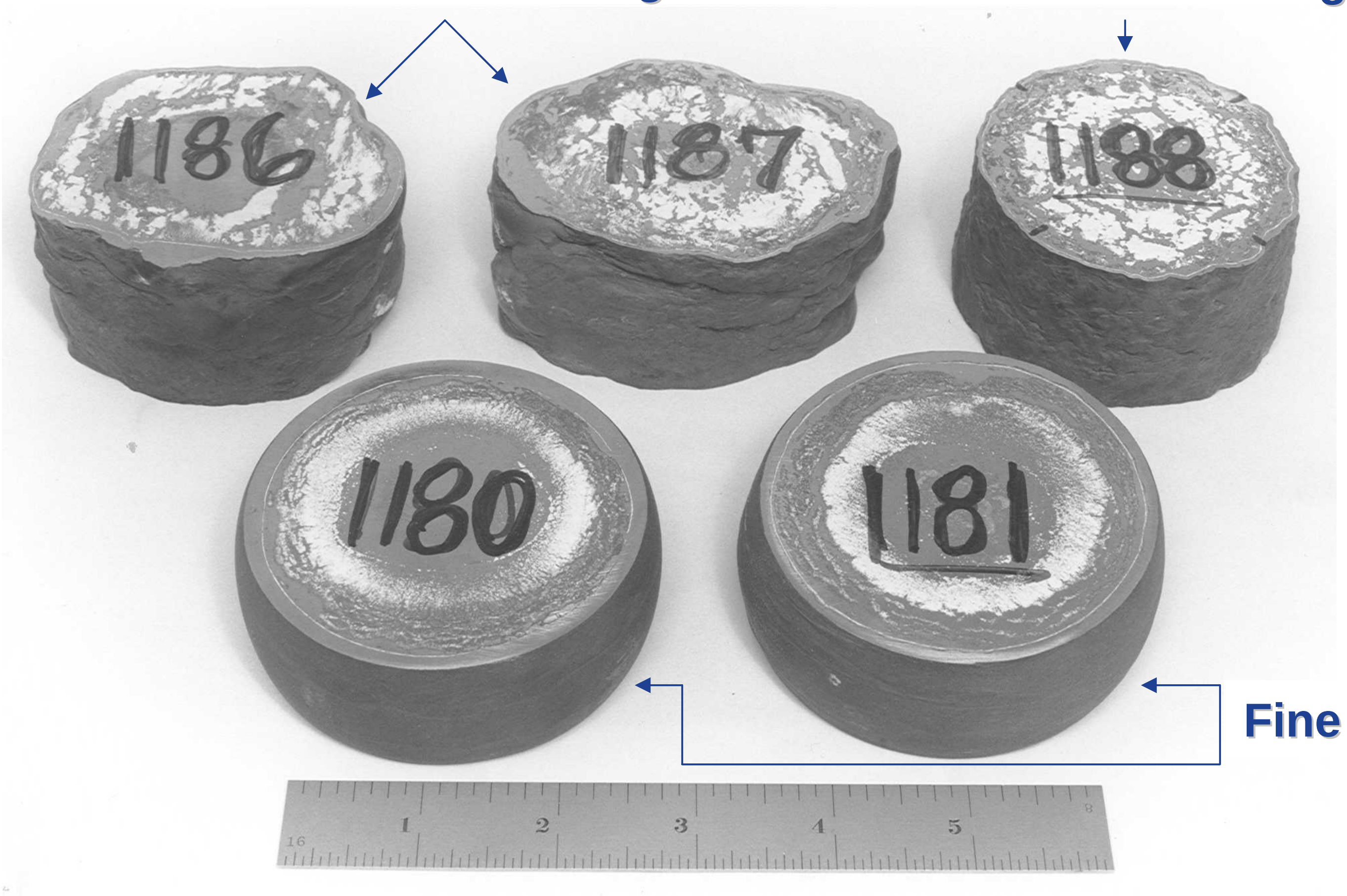
Example of a poorly converted alloy X750 billet that retains unrecrystallized dendrite cores at outer billet locations and carbide clusters.

Characterization of Ingot Deformation - Flow Behavior

Post Deformation Appearance of 2” Test Samples

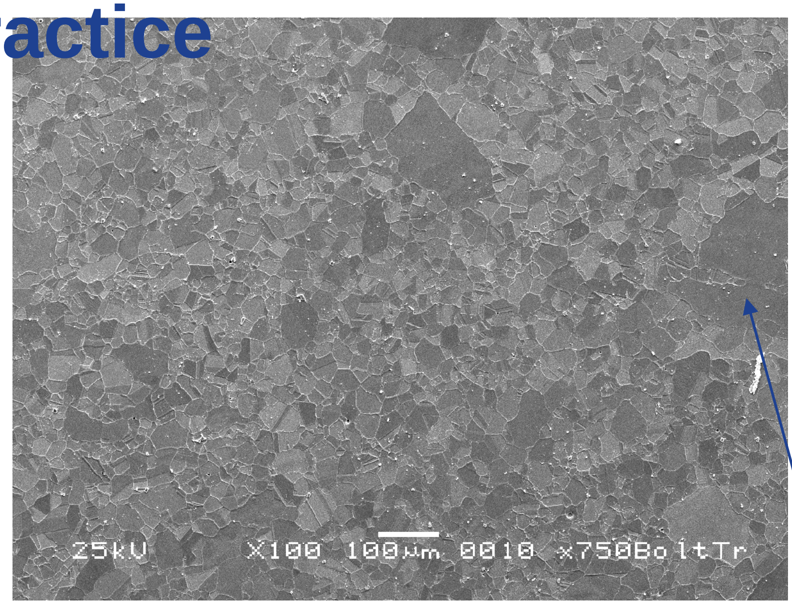
Coarse Dendrite Ingot Structure

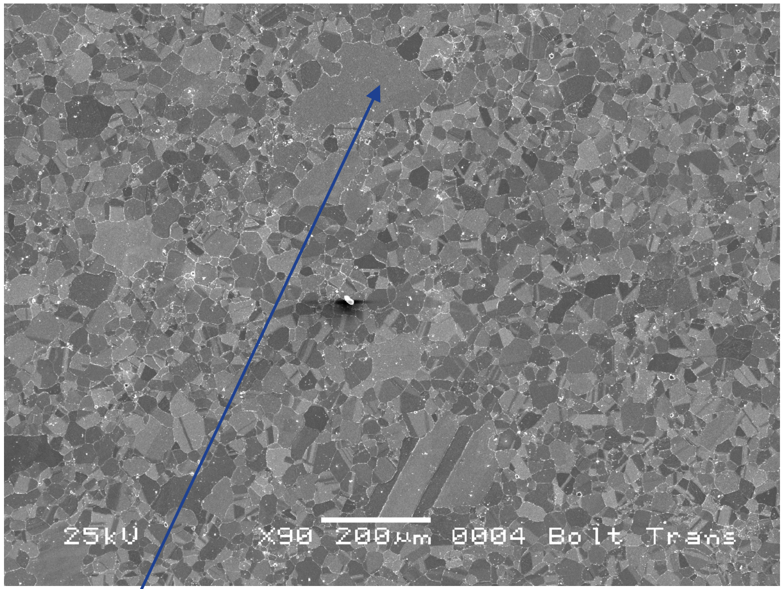
Fine Dendrite Ingot Structure

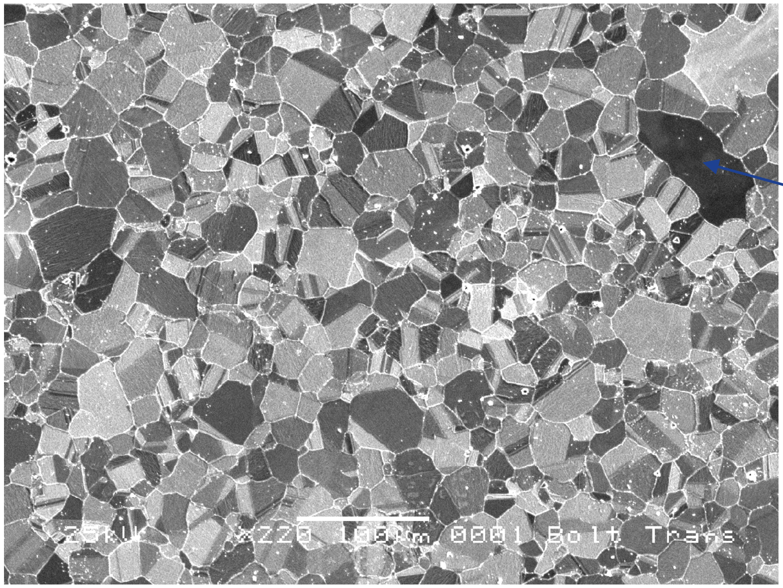


Fine Grain Billet

Unrecrystallized grains due to ingot conversion practice

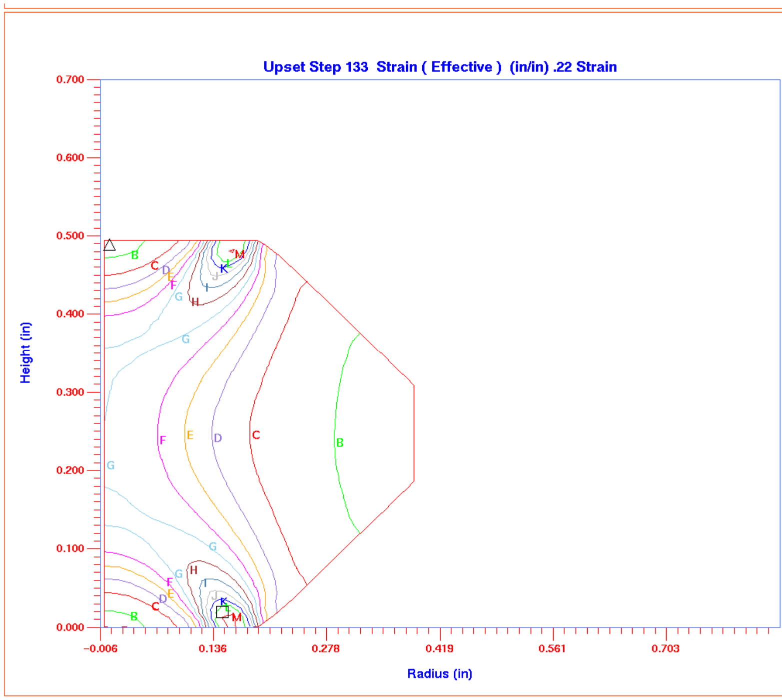


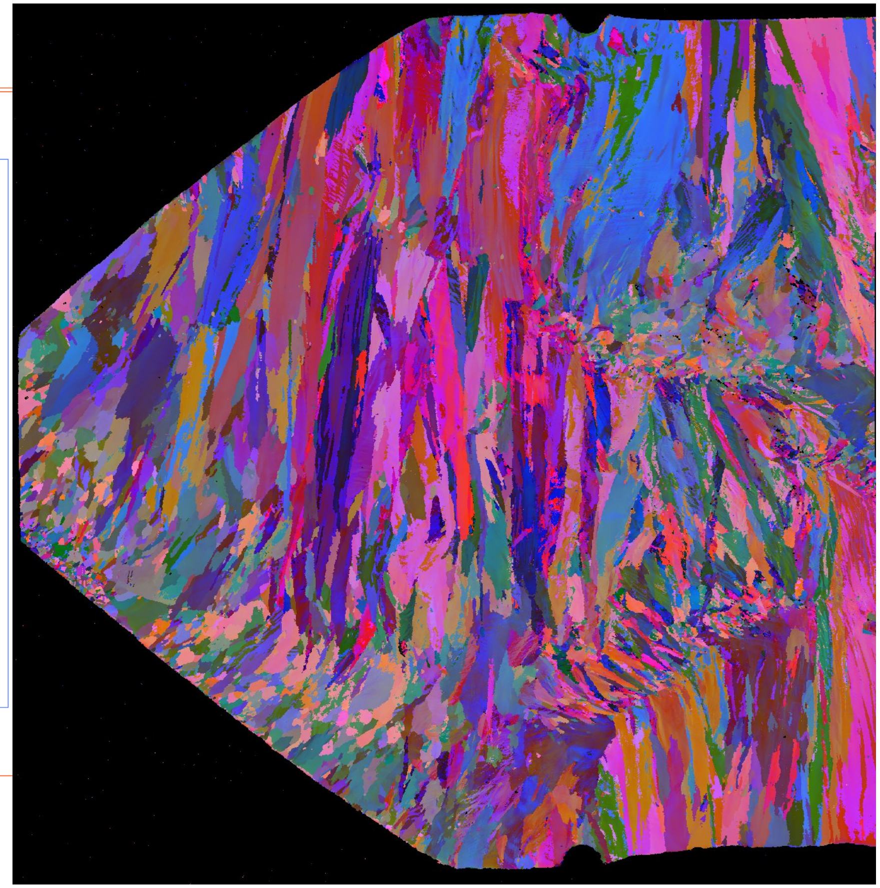


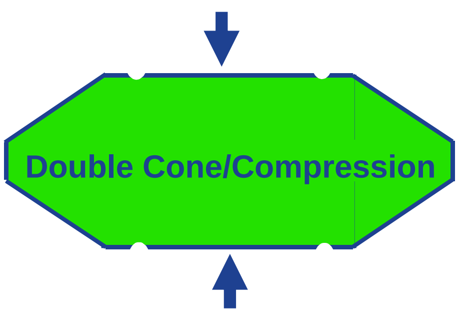


Remnant cores of unrecrystallized ingot Dendrites in X-750

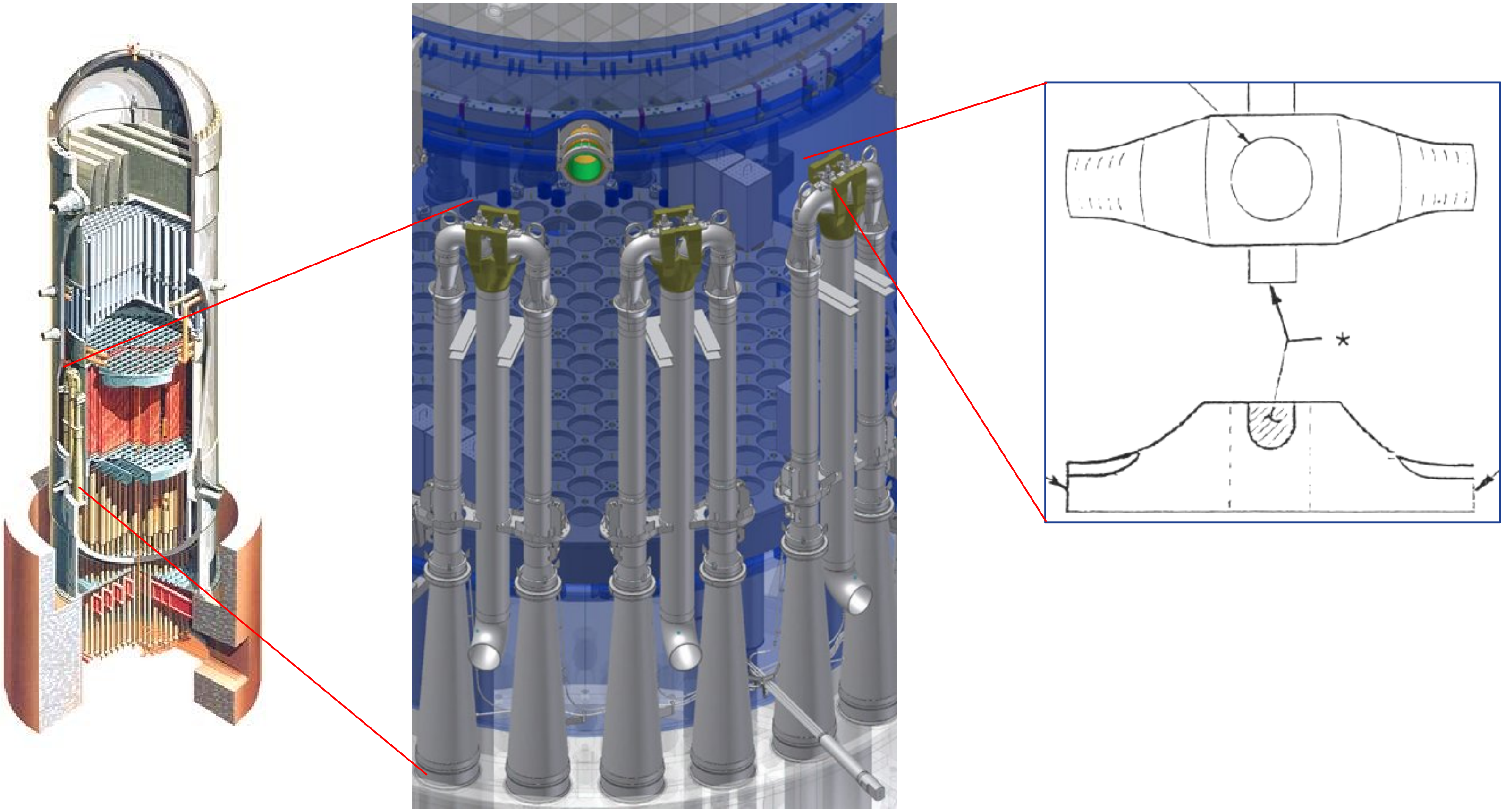
Thermal Mechanical Processing







Jet Pump Beam: Alloy X-750



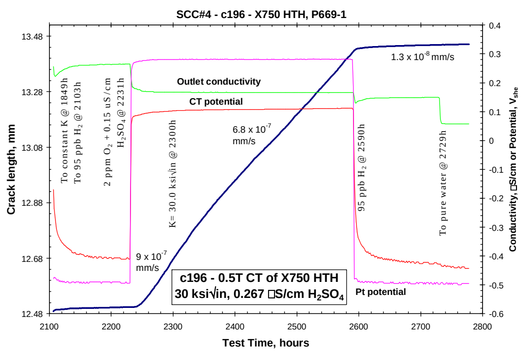
Ni-Base Superalloys

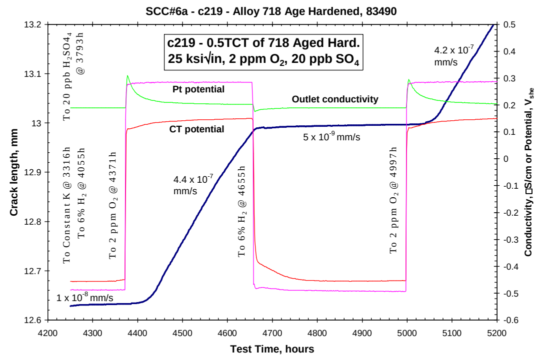
Hardening Elements

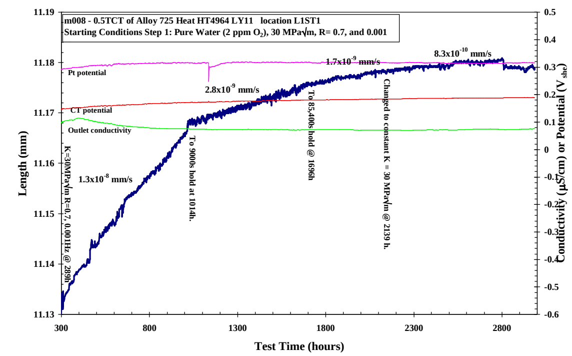
	Ni	Cr	Fe	Ti	Al	Nb	Mo	C
Alloy X-750	**70 min**	**14.0 - 17.0**	**6.5**	**2.25 - 2.75**	**0.4 - 1.0**	**0.7 - 1.2**		**0.08 max**
Alloy 718	**50.0 - 55.5**	**17.0 - 21.0**	**16.8**	**0.65 - 1.15**	**0.2 - 0.8**	**4.75**	**2.8 - 3.3**	**0.08 max**
Alloy 725	**55.0 - 59**	**19 - 22.5**	**bal**	**1.0 - 1.7**	**0.35 max**	**2.75 - 4.0**	**7.0 - 9.5**	**0.03 max**

	Ti, Al	Nb
	$Ni_3(Al, Ti, Cr)$	Ni_3Nb
Hardening Phases	γ ' – meta stable	γ " – meta stable
Grain Size Control Phases	η– Ni_3Ti - stable	δ - stable
Carbide Phases	$Cr_{23}C_6$ NbC TiNb(C,N)	

Comparison: SCC Growth in Alloys X-750, 718 & 725







X-750 718 725

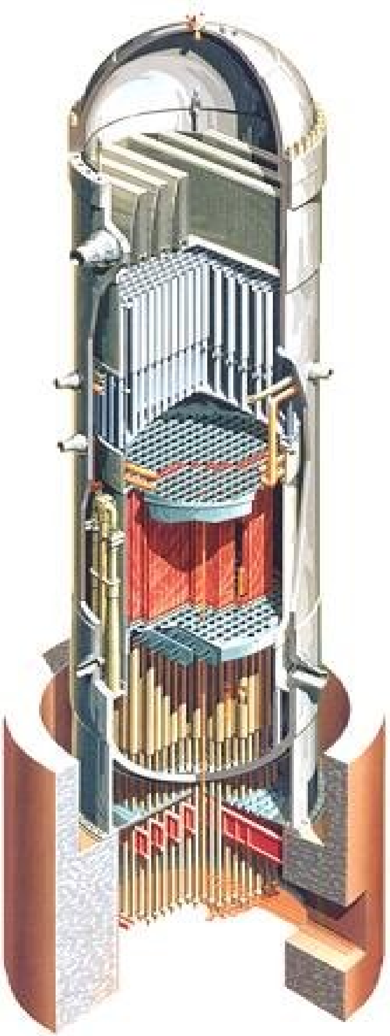
Alloy	High ECP	Low ECP
X-750	**6.8×10^{-7}**	**1.3×10^{-8}**
718	**4.4×10^{-7}**	**5.0×10^{-9}**
725	**$<8.3 \times 10^{-10}$**	**------**

Units (mm/s)

Significant reduction in SCC in alloy 725 vs. alloys X-750 and 718

Crack Initiation

SCC Initiation Mitigation



Desirable Surface Improvement Traits:

- Creates a compressive surface stress
- Removes surface and subsurface defects
- Does not alter the properties of the alloy
- Leaves a smooth defect free surface

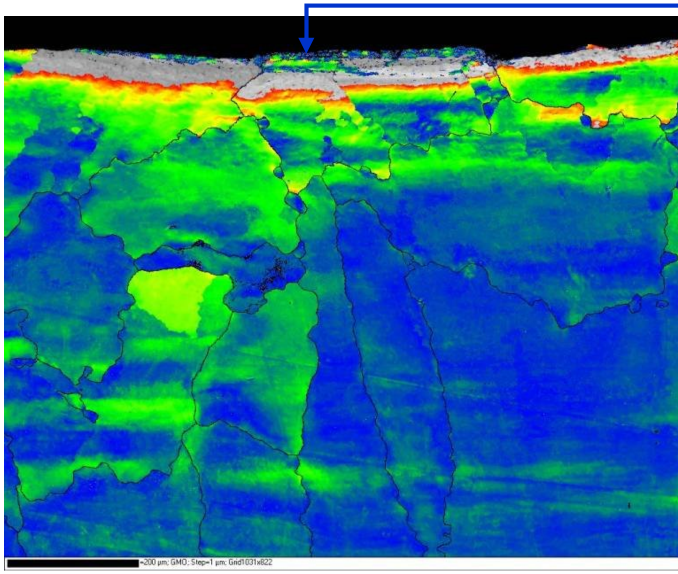
SCC in Weldments

Contributing factors introduced during original fabrication processes:

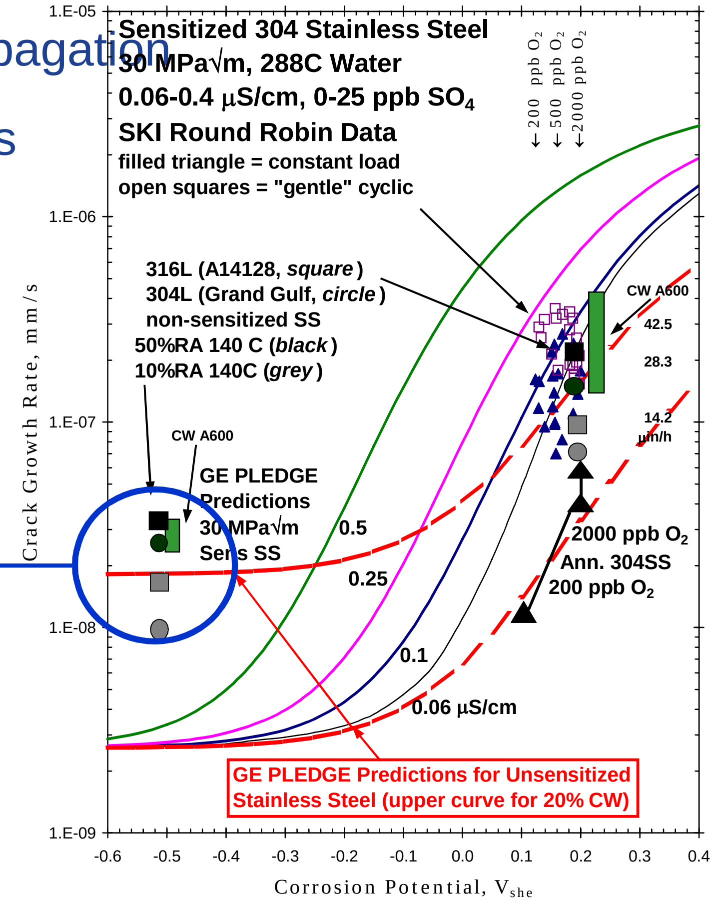
Cold worked surface layers – residual plastic strain enhances SCC growth rate

High tensile residual stresses – drives SCC propagation

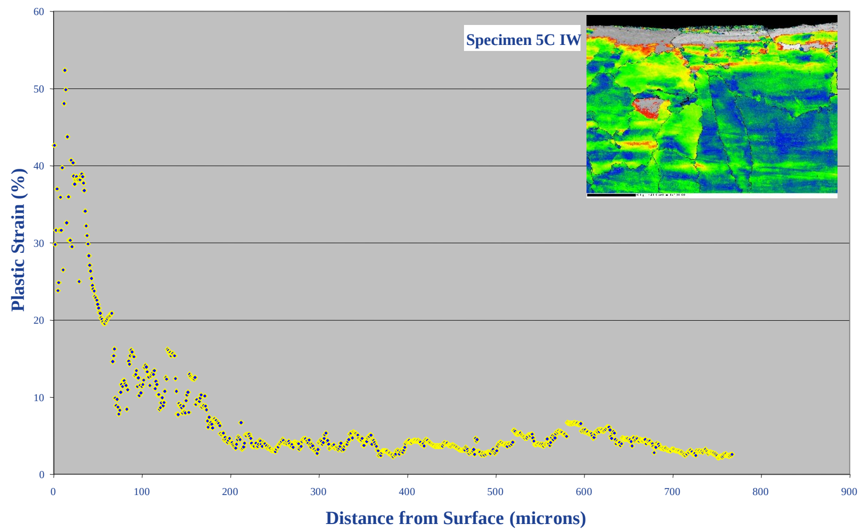
Surface roughness – provides SCC initiation sites

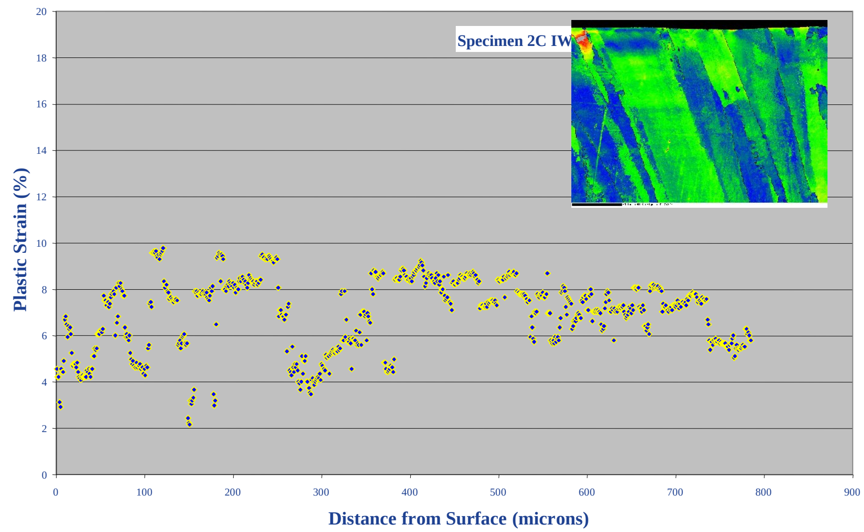


Plastic strain induced surface damage to weld metal structure



Surface Conditioning with ReNew™ Process



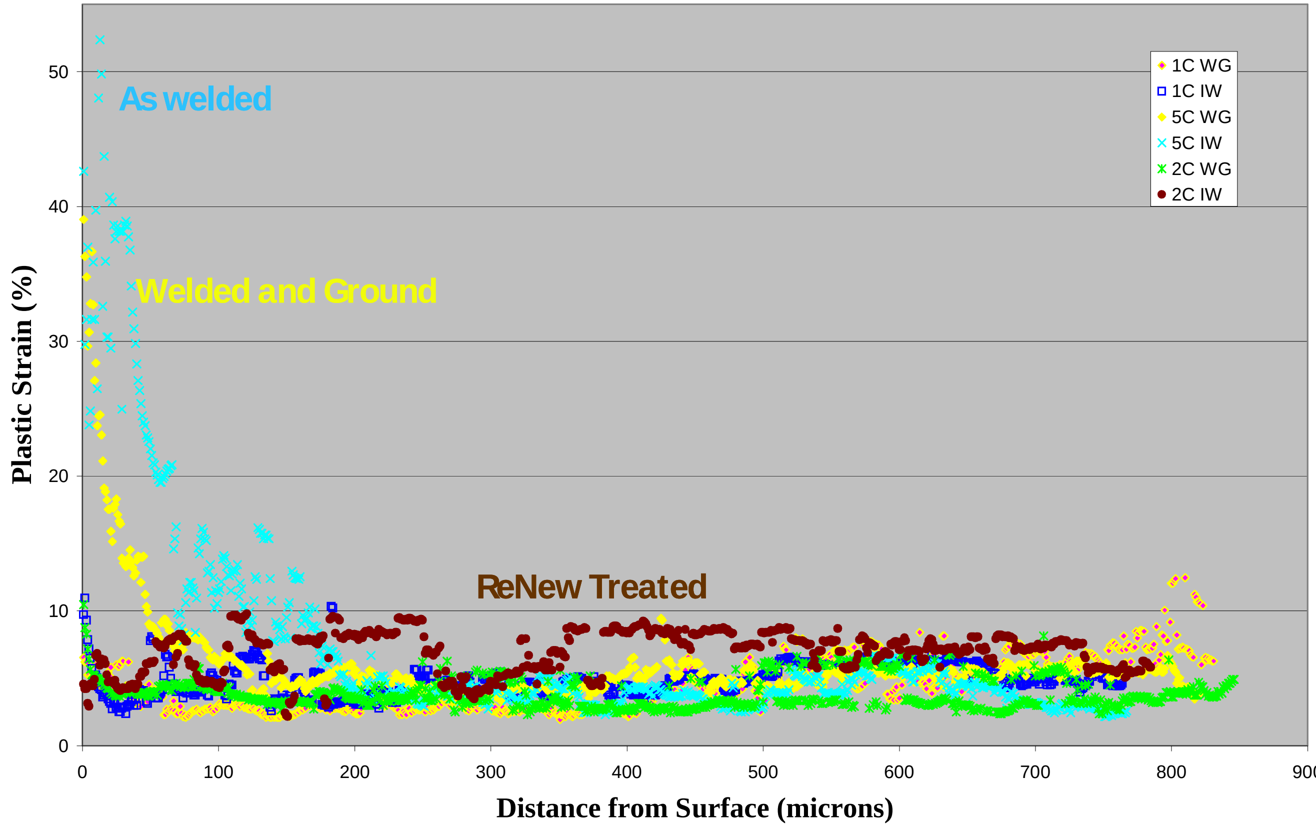


As Welded

ReNew™ Treated

Residual plastic strain due to welding is drastically reduced with ReNew process

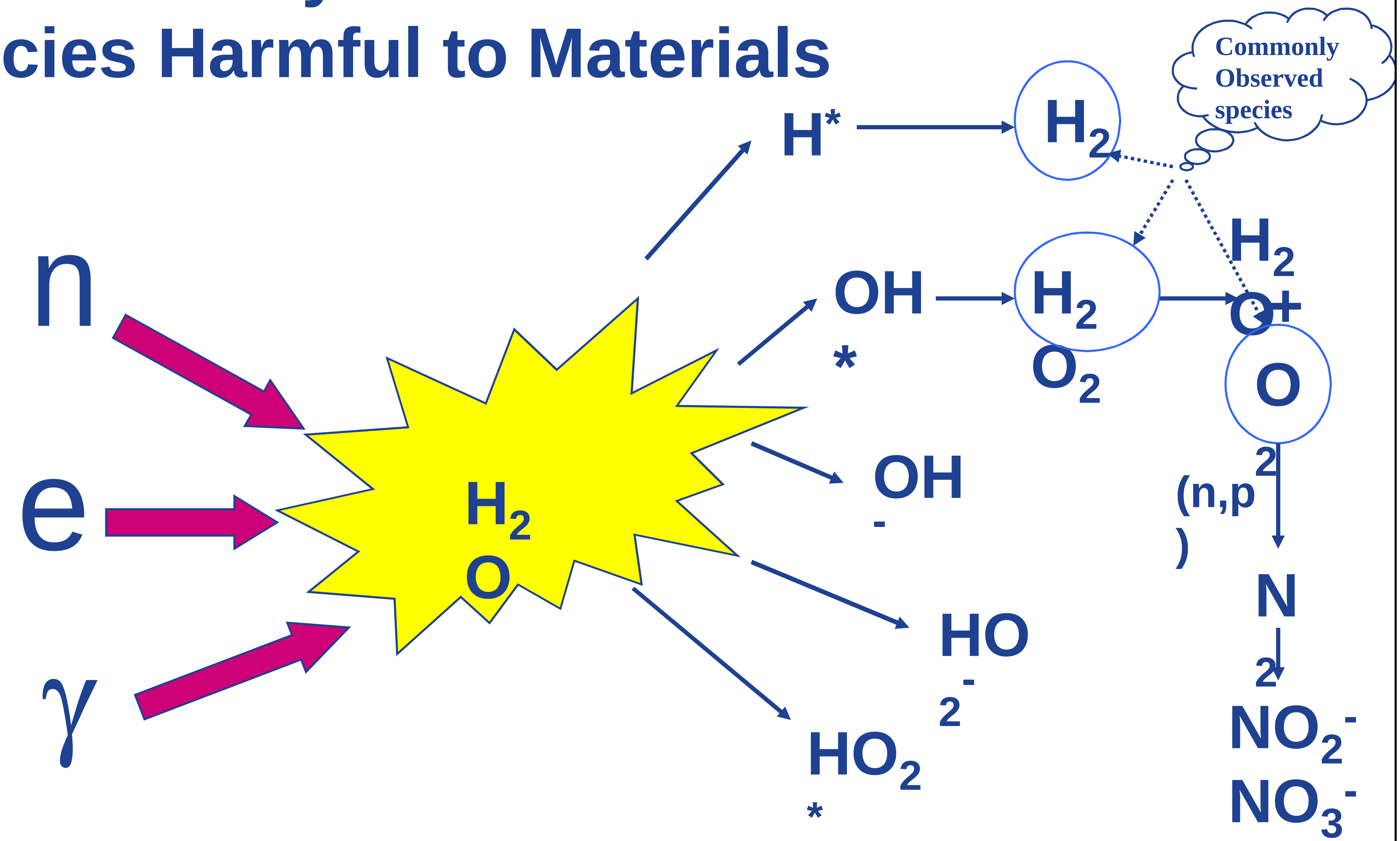
Surface Conditioning with ReNew™ Process



Residual plastic strain reduced, SCC initiation resistance improved

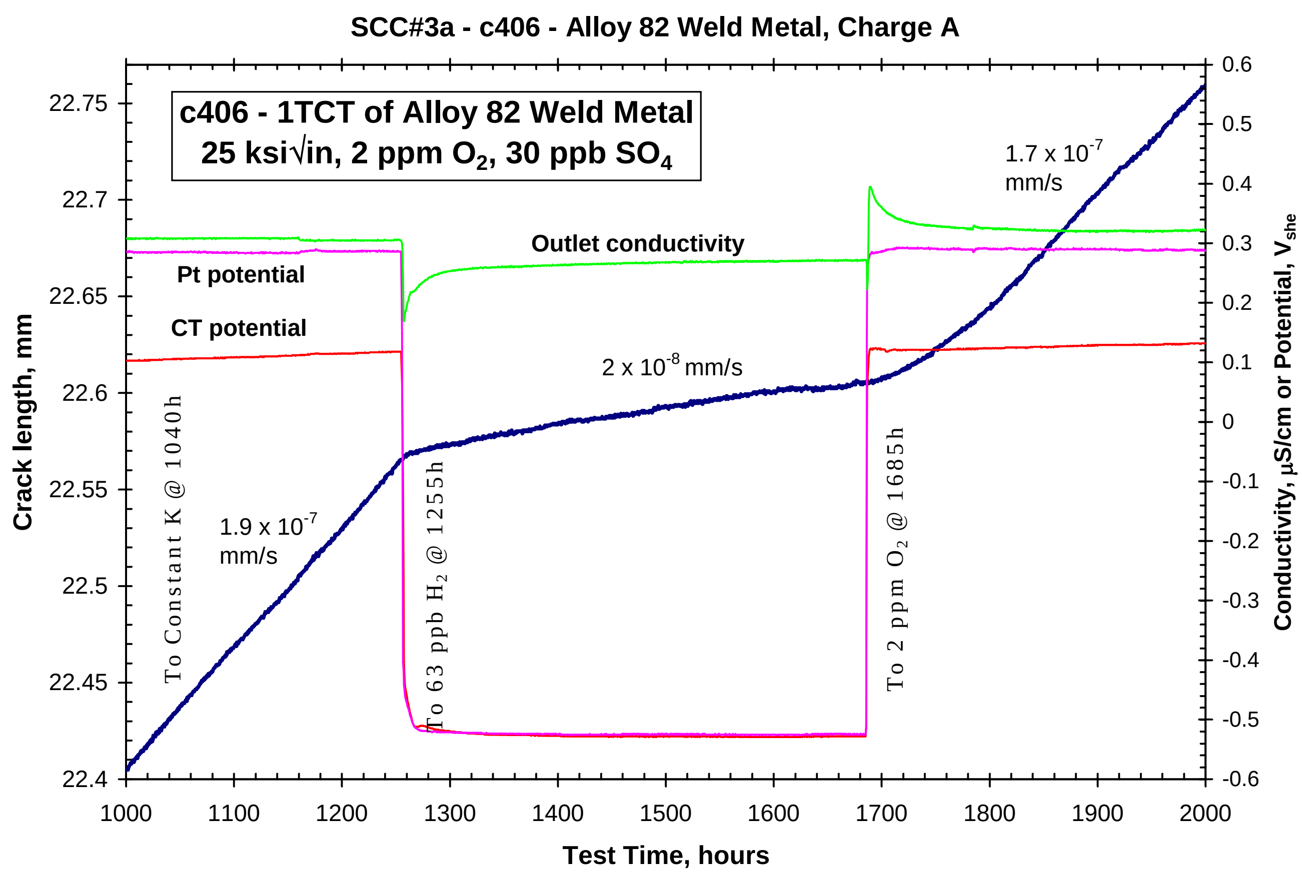
ECP Monitoring & NobleChem™

Water Radiolysis Generates Species Harmful to Materials



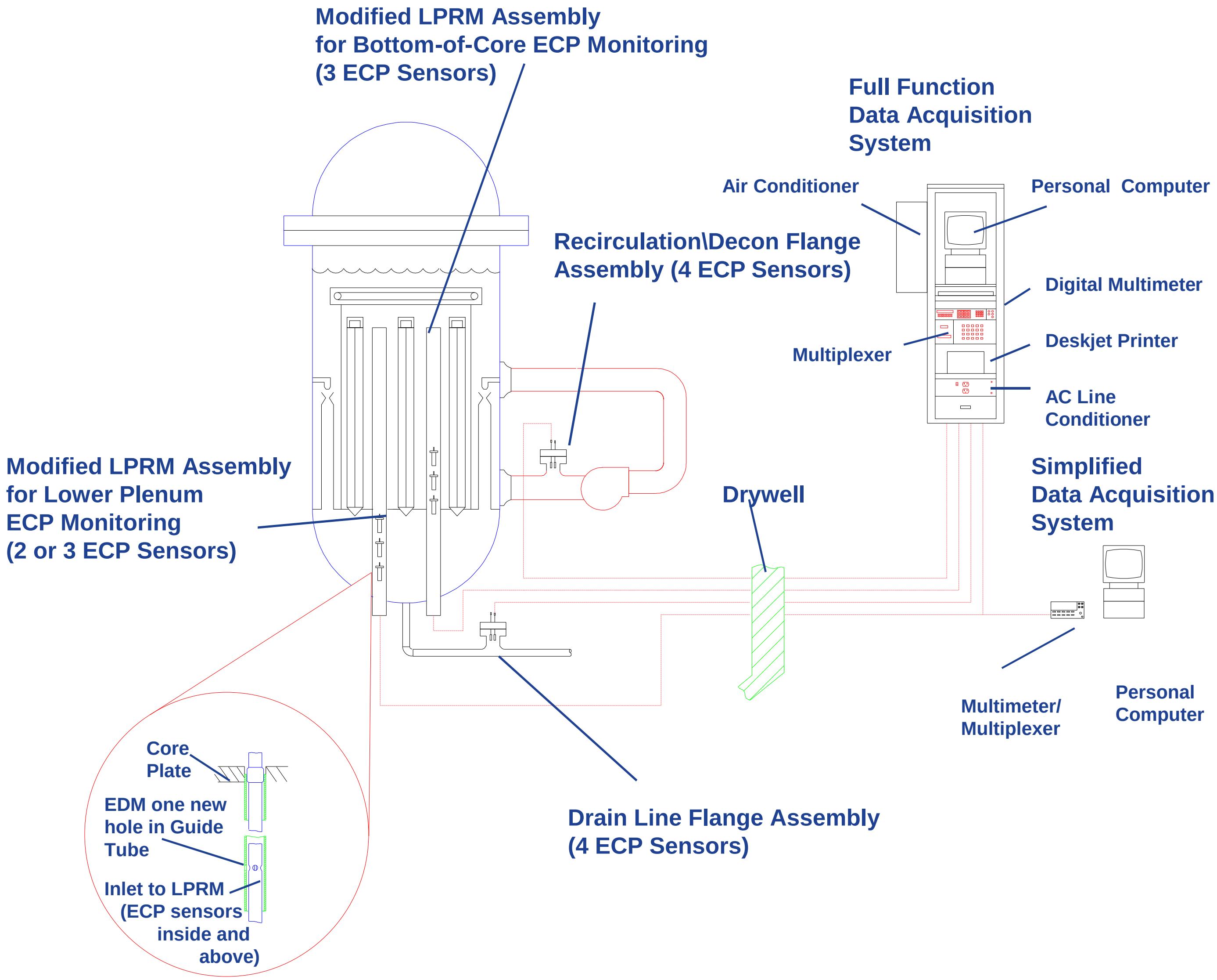
Oxidant (H_2O_2 and O_2) Generation By Water Radiolysis

Effect of ECP on Crack Growth Rate

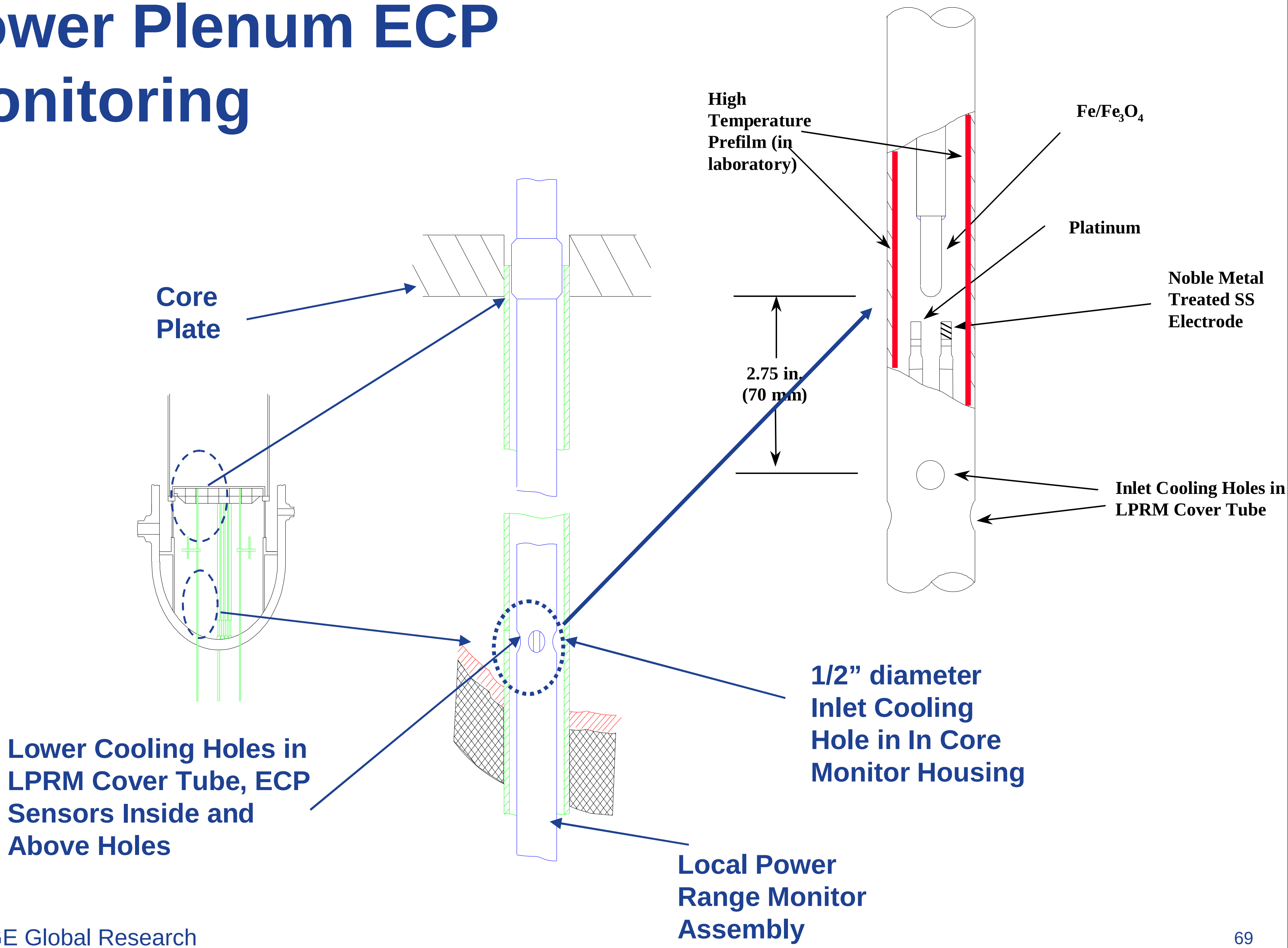


Strong Effect of Corrosion Potential

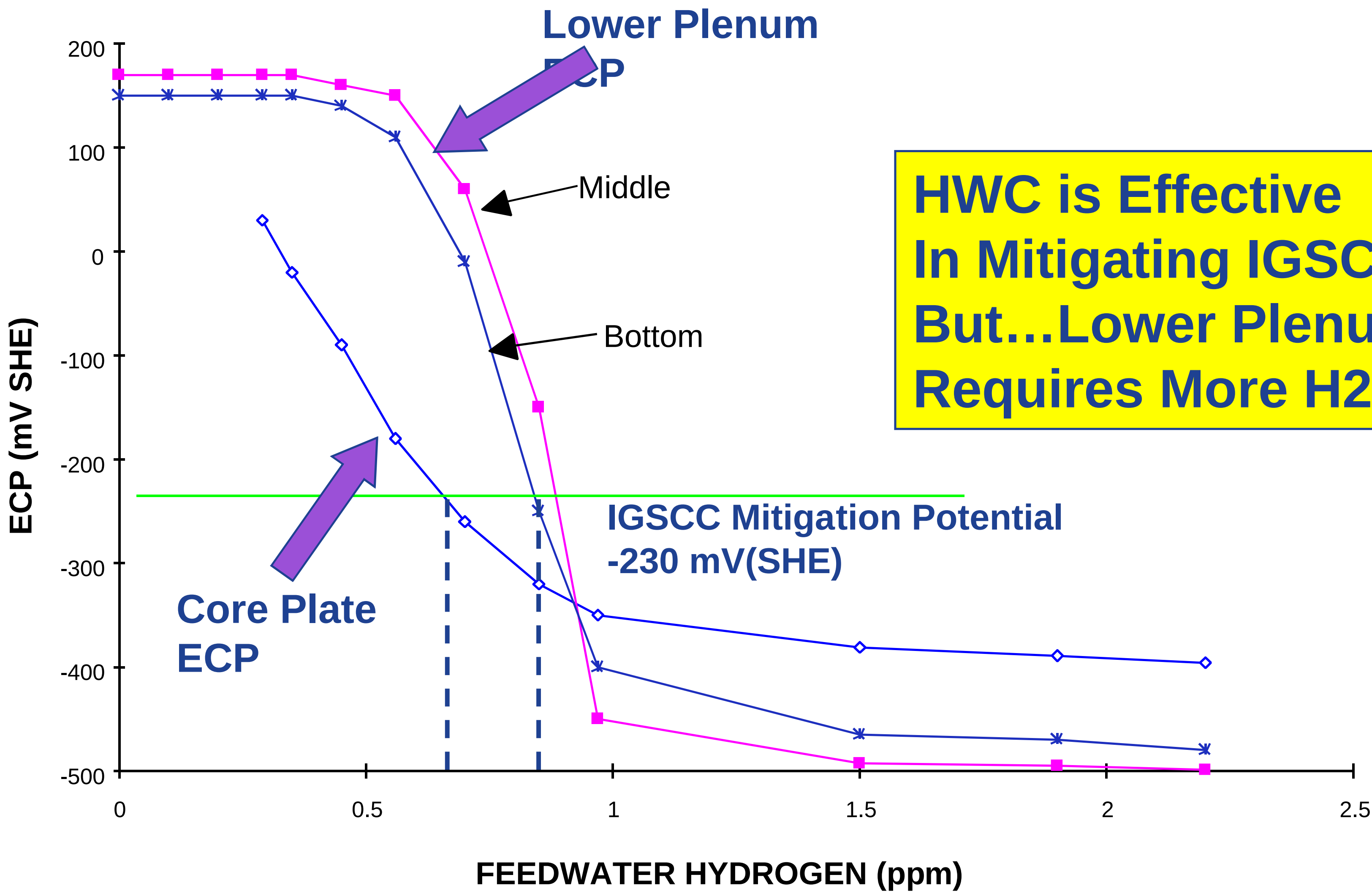
BWR ECP Monitoring Locations



Lower Plenum ECP Monitoring

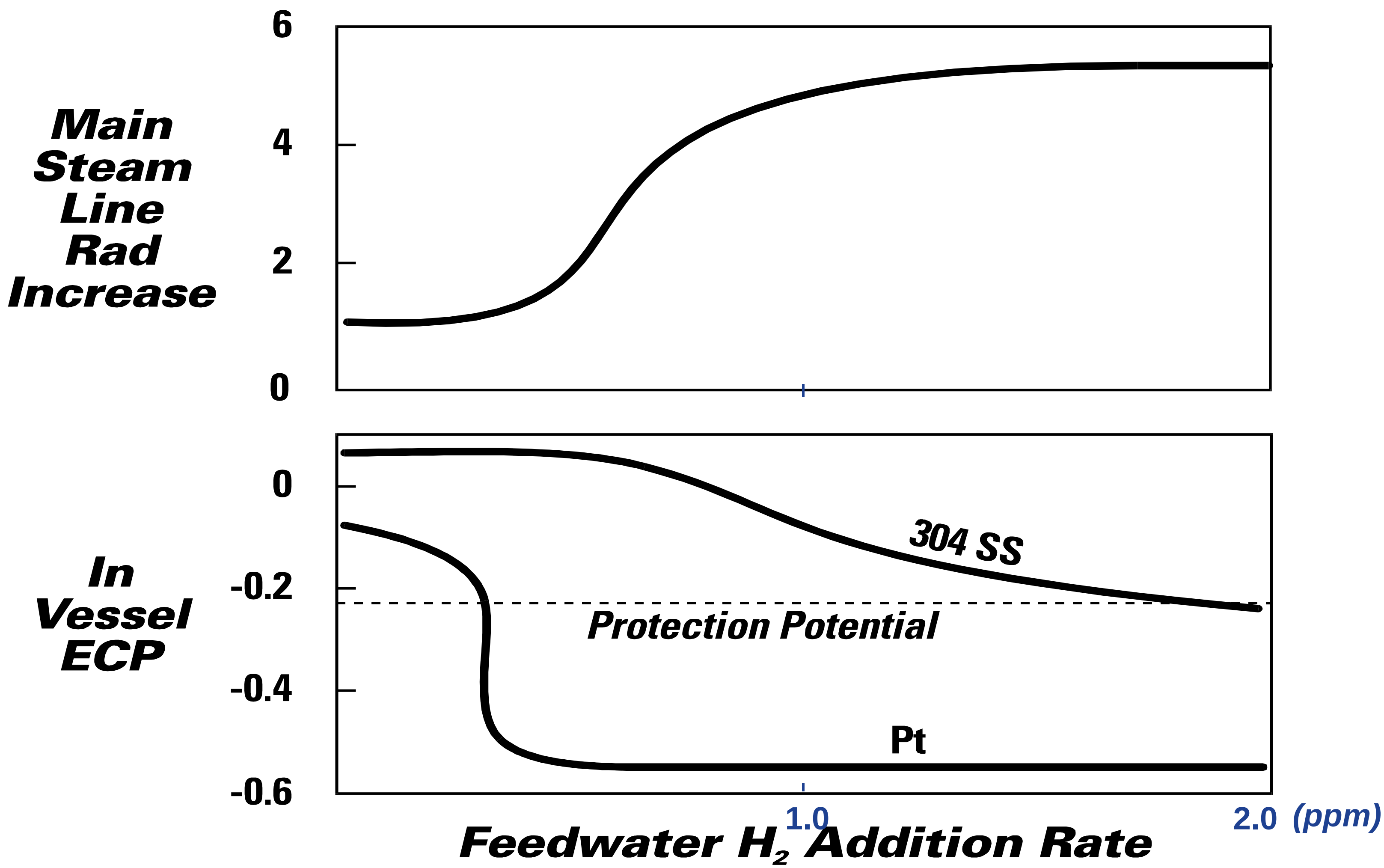


Bottom Plenum ECP Response

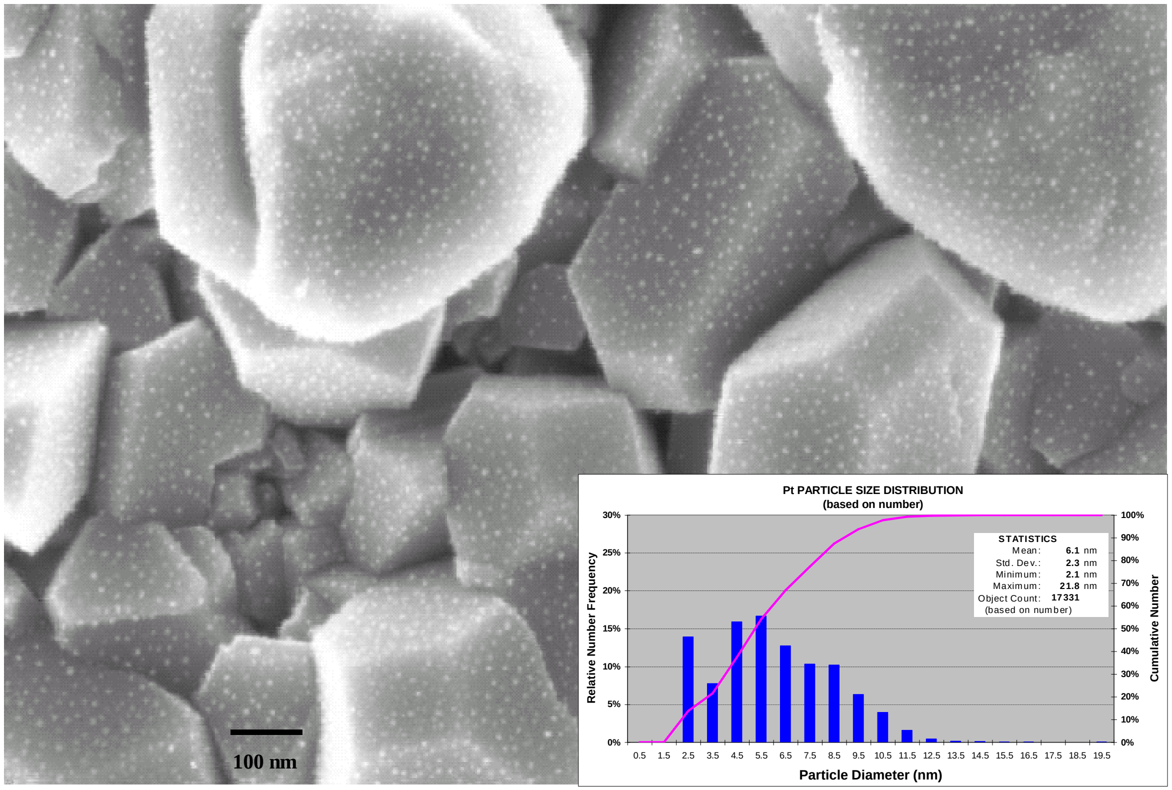


HWC is Effective In Mitigating IGSCC But…Lower Plenum Requires More H2

Basis for NobleChem™ Technology

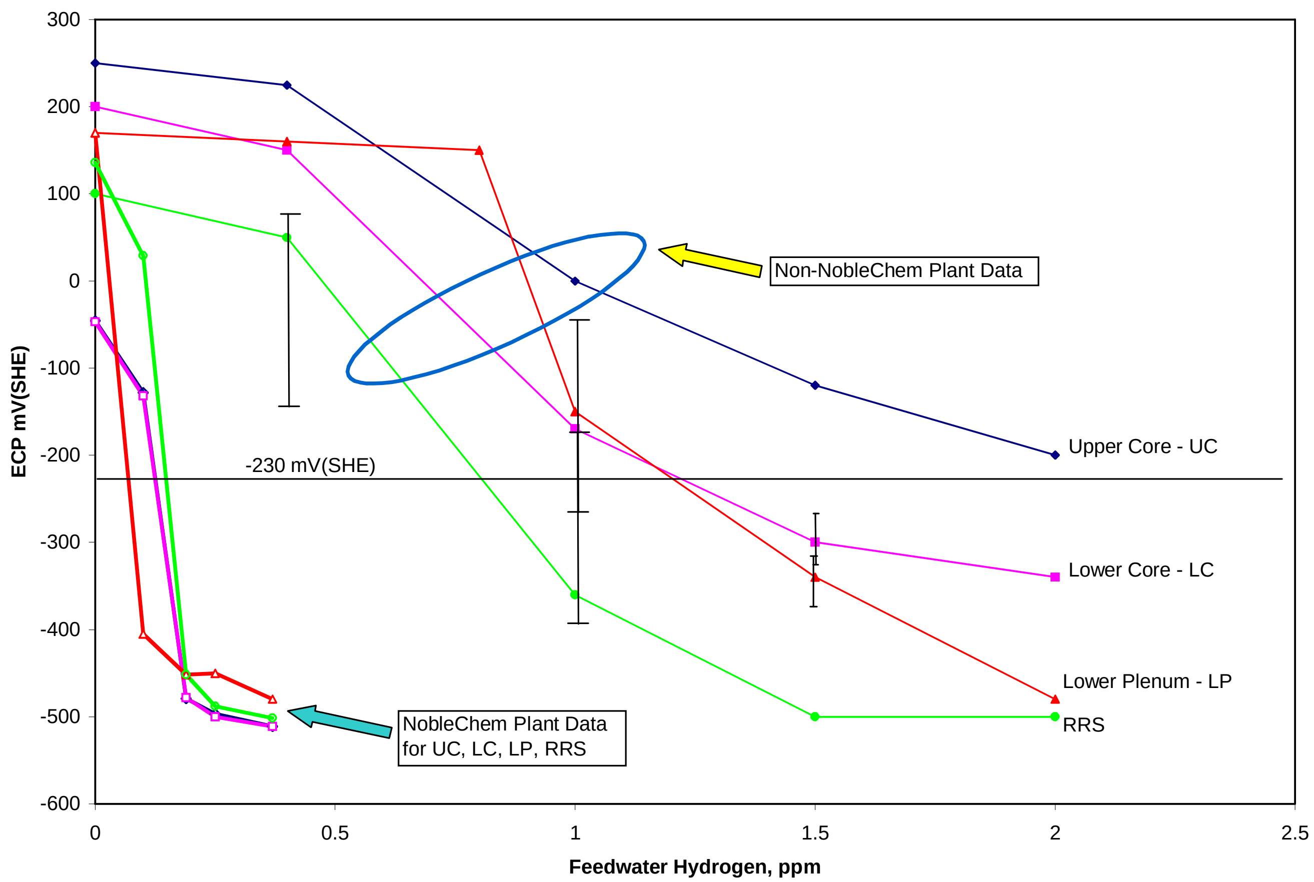


Noble Metal Distribution After On-Line Application



Nano-particle Pt Generation By On-Line NobleChem™

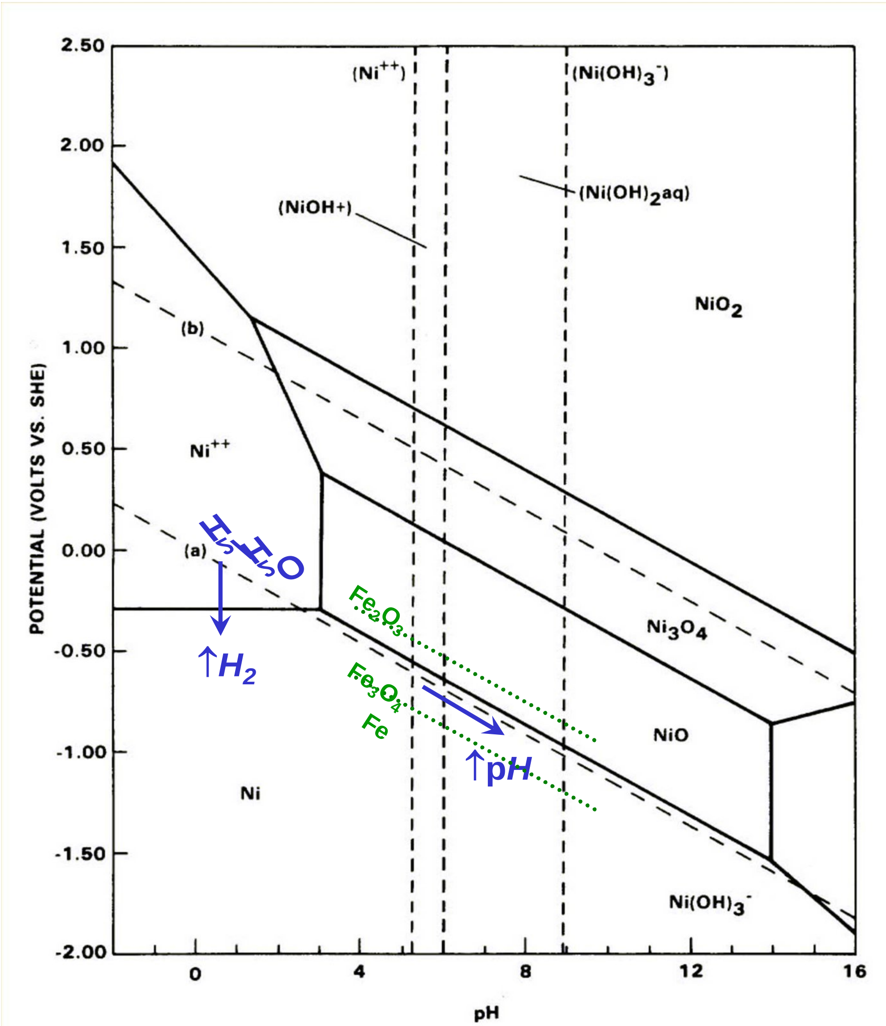
ECP Reduction With NobleChem™



Provides Low ECPs At All Internal Locations

PWR Water Chemistry & Cracking Issues

Role of H_2 and B/Li/pH Water Chemistry

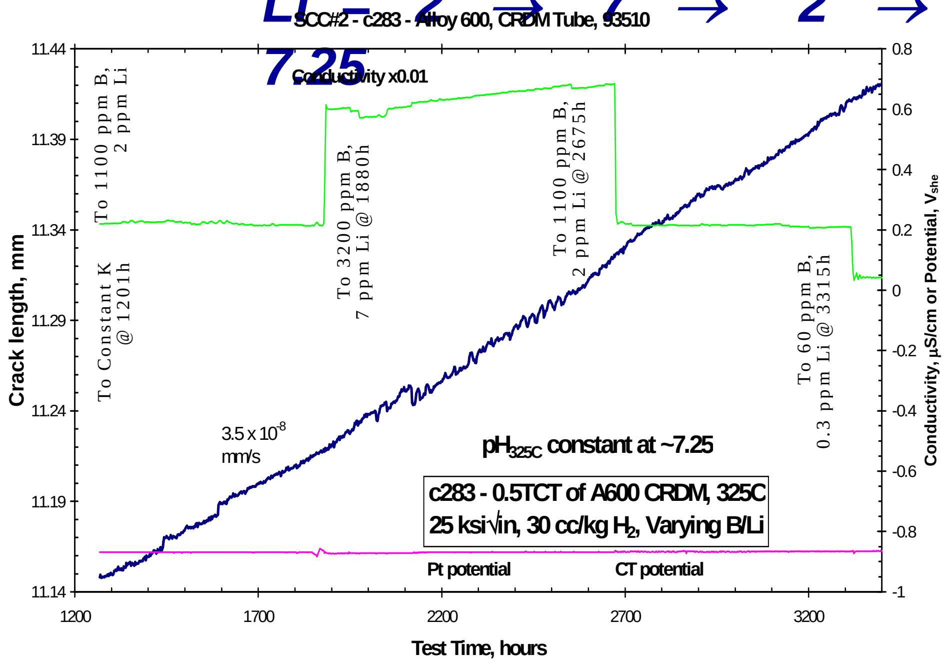


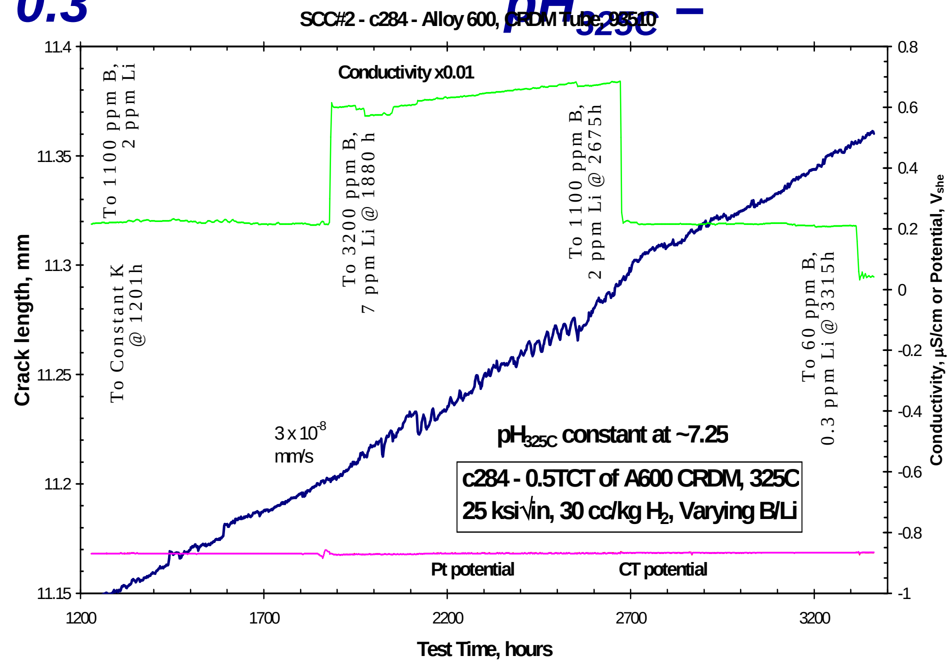
- **Connection between BWR & PWR leverages data & understanding**
- **Extensive PWR data – applicable because B/Li/pH is not important in deaerated water**
- **There is a ~16X peak vs. H_2 for Alloy 82/182 weld metal that is relevant to BWRs**

B/Li Effects at Constant pH

B = 1100 → 3200 → 1100 → 60 ***pH_{300C} = 6.9***

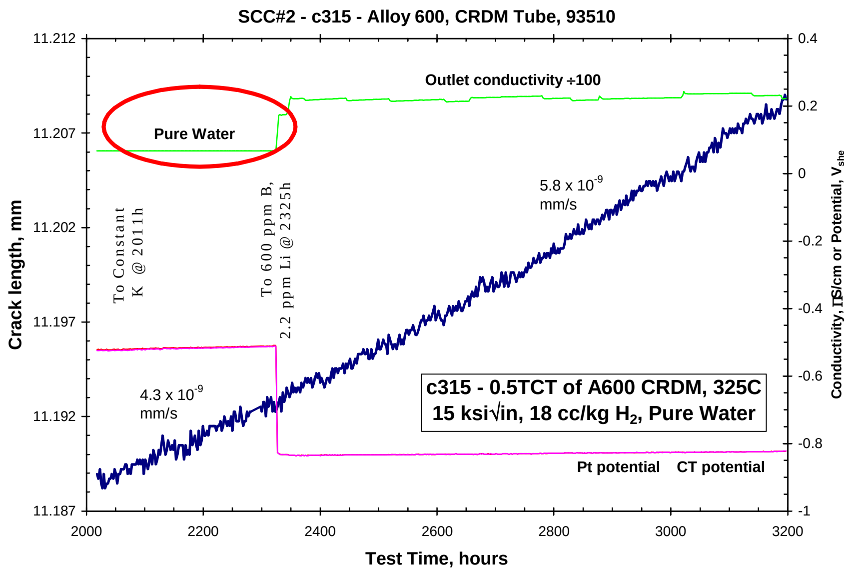
Li = 2 → 7 → 2 → 0.3 ***pH_{325C} = 7.25***

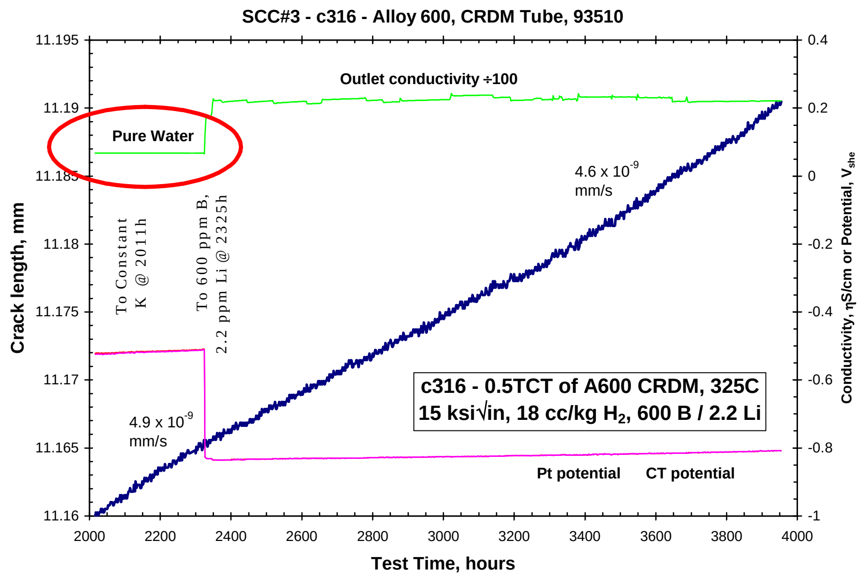




No effect on CGR of wide range of B/Li/pH_T in deaerated water. Expect PWR primary ≈ BWR low potential, with correction for T & H_2

B/Li Effects At Varying pH



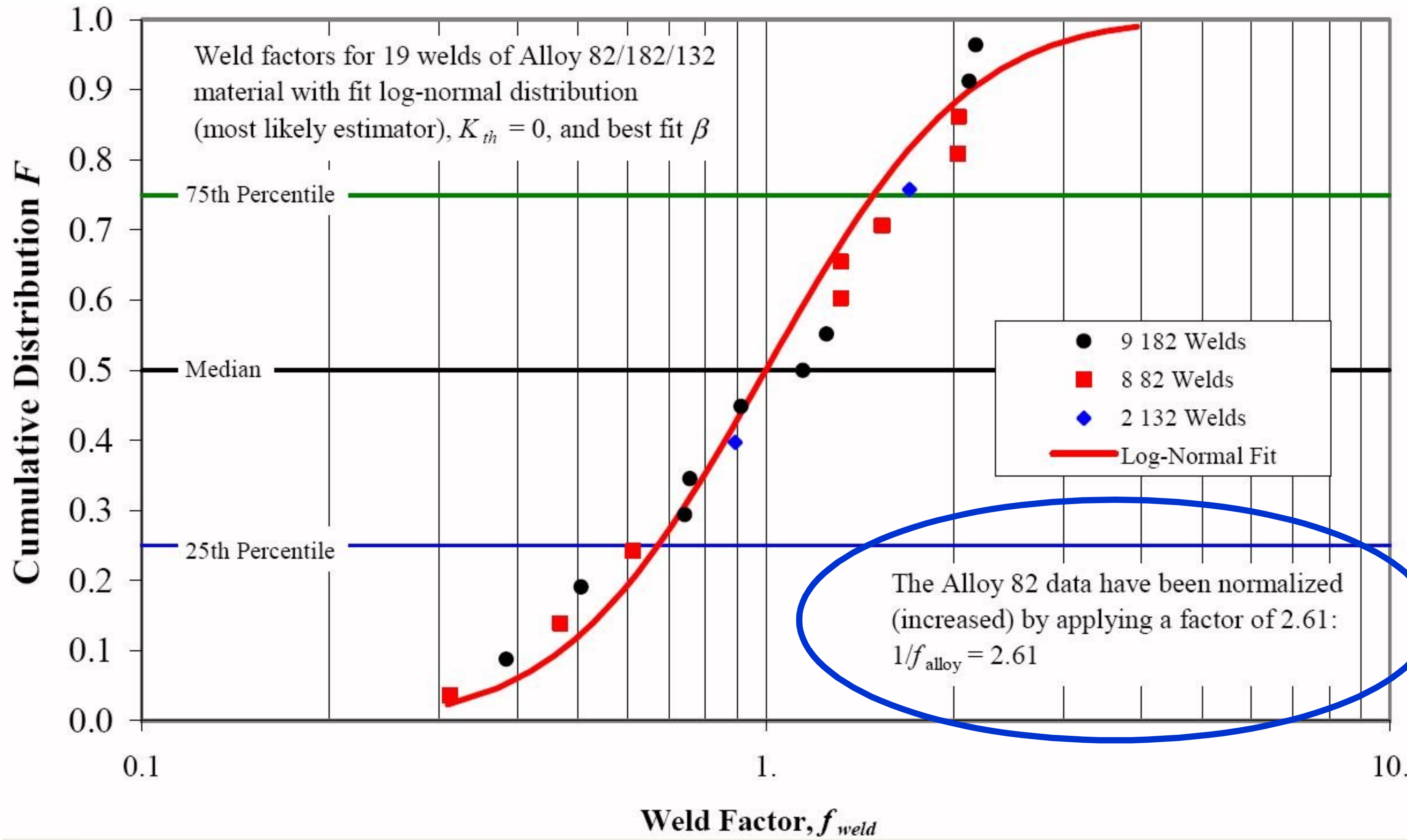


No effect of B/Li chemistry

Pure water $\rightarrow$ 600B / 2.2Li

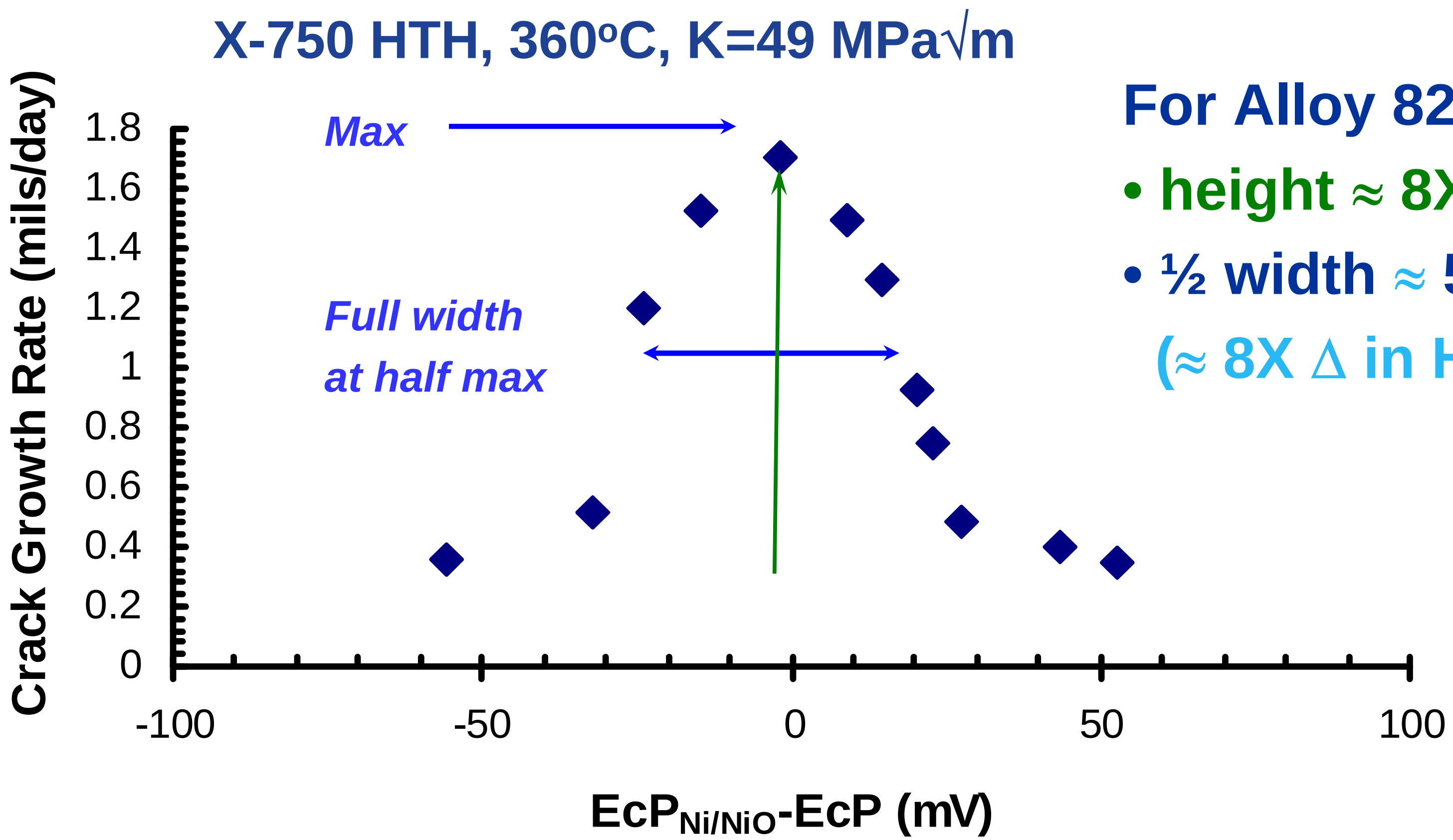
pH_{325C} = 5.86 $\rightarrow$ 7.53

EPRI Analysis on Alloy 82 & 182/132 in PWRs



Alloy 82 only shows 2.6X CGR difference vs. Alloy 182.
Expect PWR primary ≈ BWR low potential, with correction for T & H_2

Ni Alloy Crack Growth Rate vs. H_2



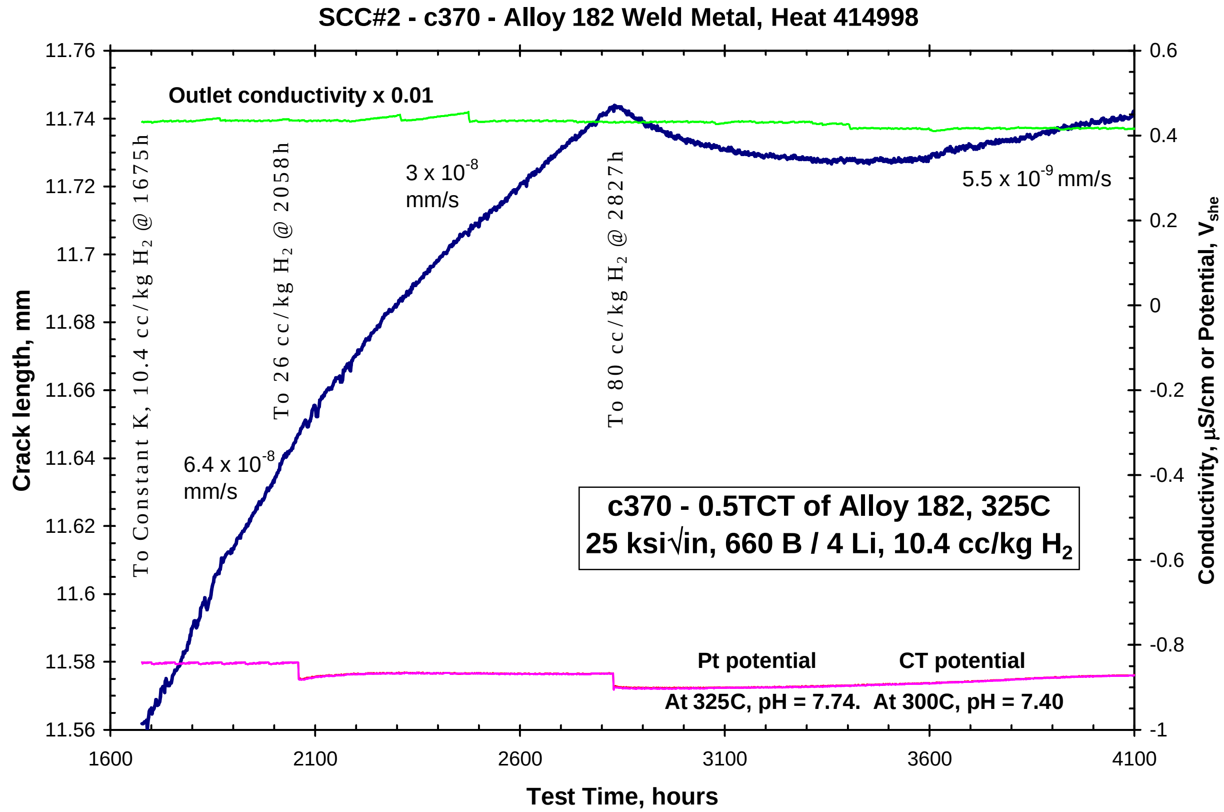
For Alloy 82:

- **height ≈ 8X**
- **½ width ≈ 50 mV**

(≈ 8X Δ in H_2)

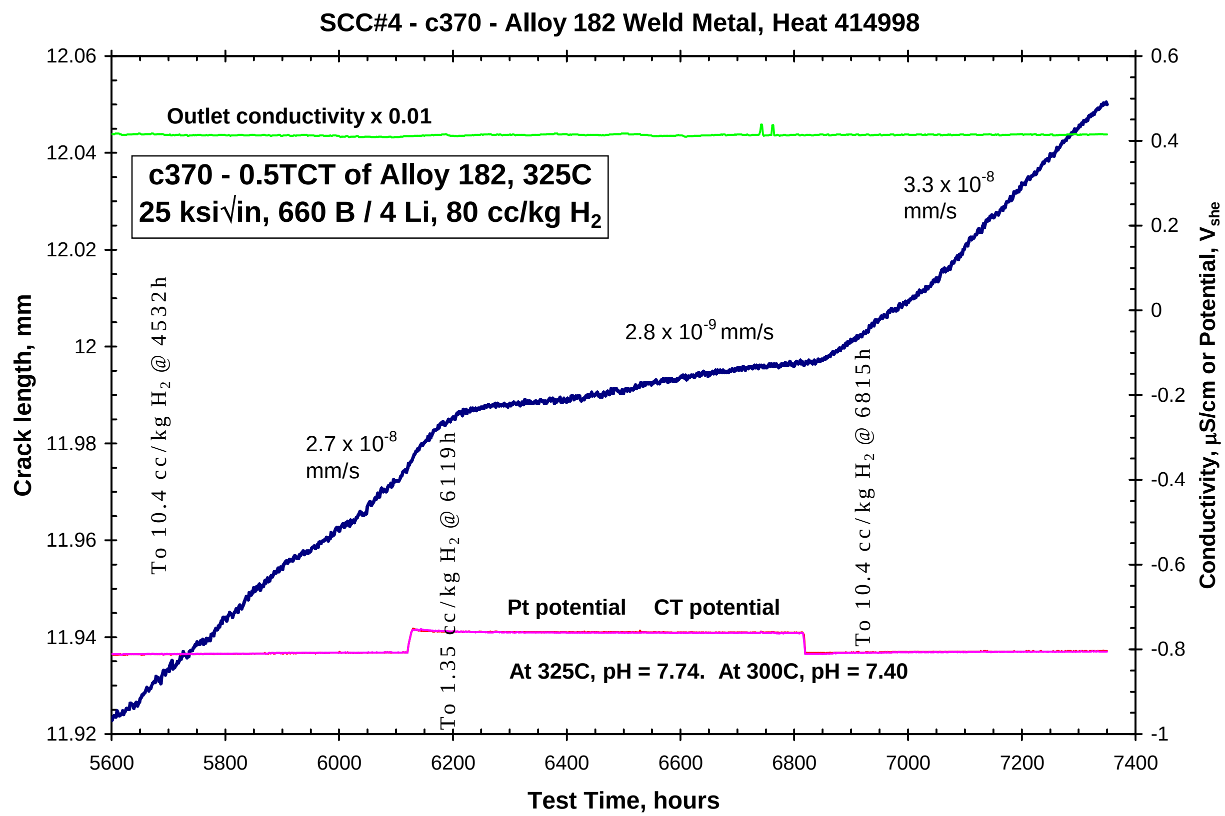
KAPL data: consistent benefit of ↑H_2 250 – 360 C

H_2 Effects on SCC of Alloy 182 Weld



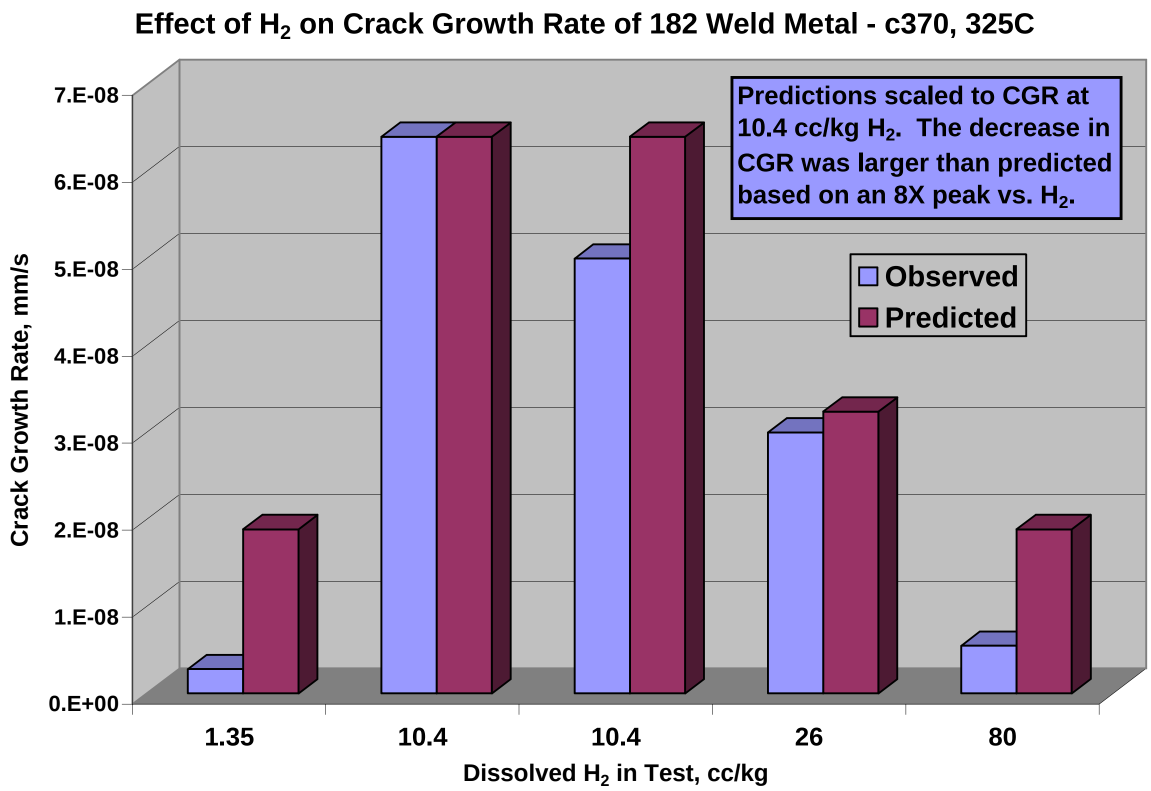
The change to 80 cc/kg H_2 causes short term decrease in crack length in dc potential drop due Ni-metal formation in crack

H_2 Effects on SCC of Alloy 182 Weld



The change to 1.35 cc/kg H_2 causes short term decrease in crack length, then more rapid short term increase as H_2 is reduced to 10

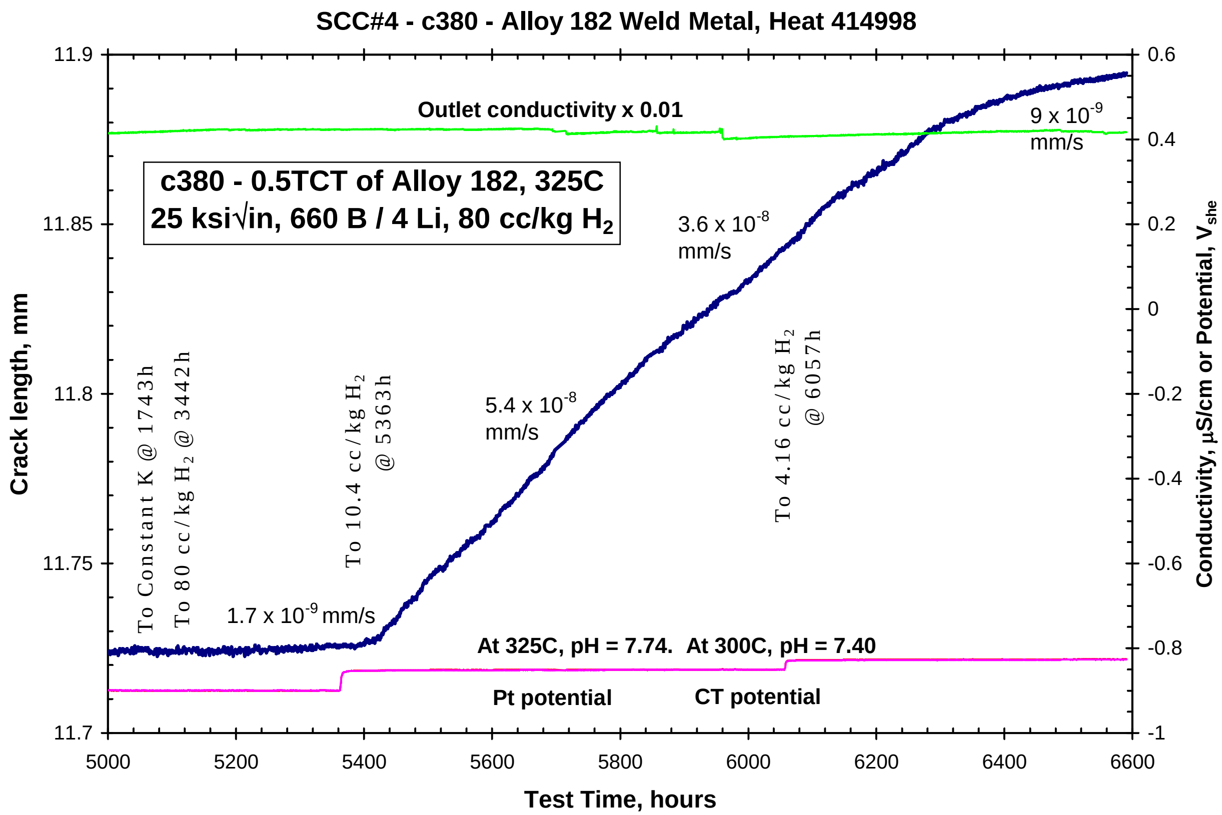
H_2 Effects on SCC of Alloy 182 Weld



Peak (Ni/NiO boundary) at 325C is 10.4 cc/kg H_2

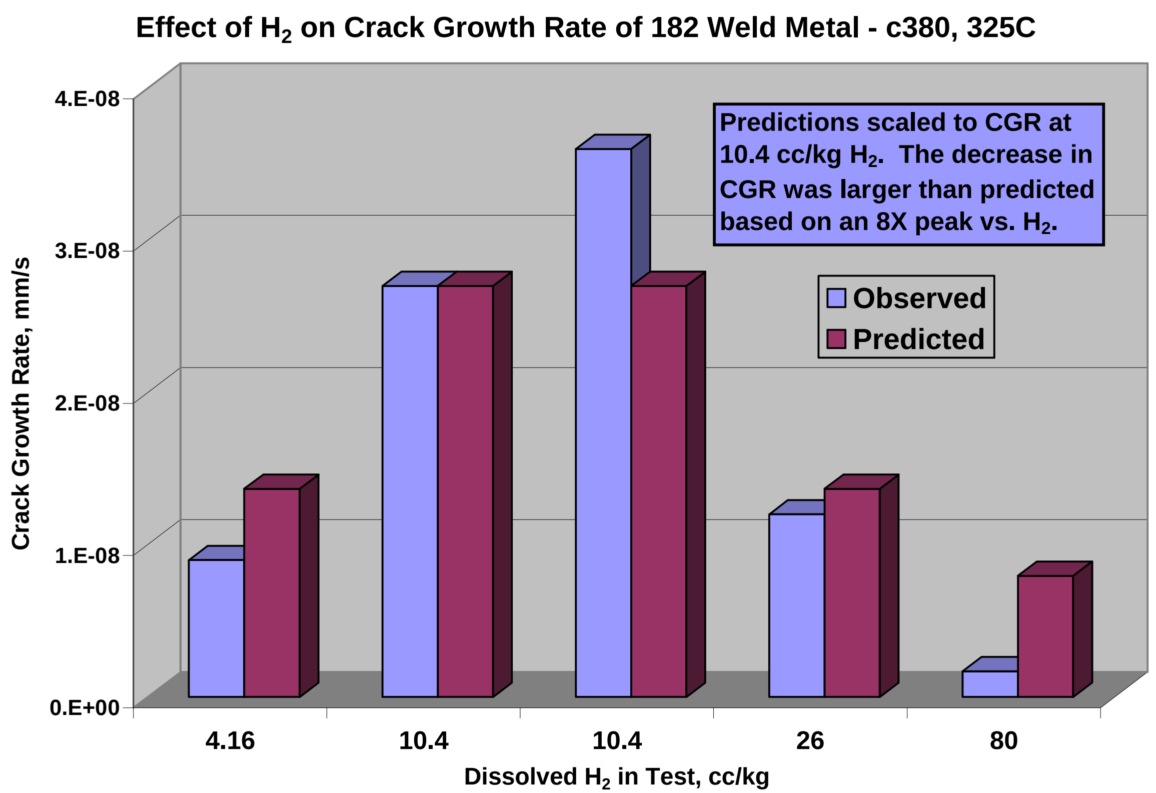
Observed a larger effect than predicted from an "8X peak"

H_2 Effects on SCC of Alloy 182 Weld



The change to 80 cc/kg H_2 causes short term decrease in crack length – more time needed to get steady-state growth rate.

H_2 Effects on SCC of Alloy 182 Weld



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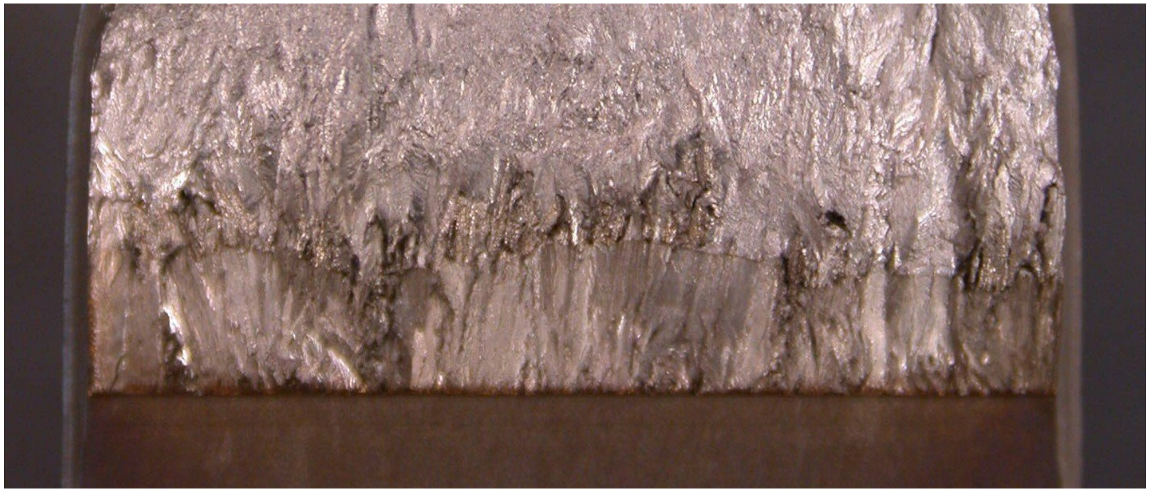
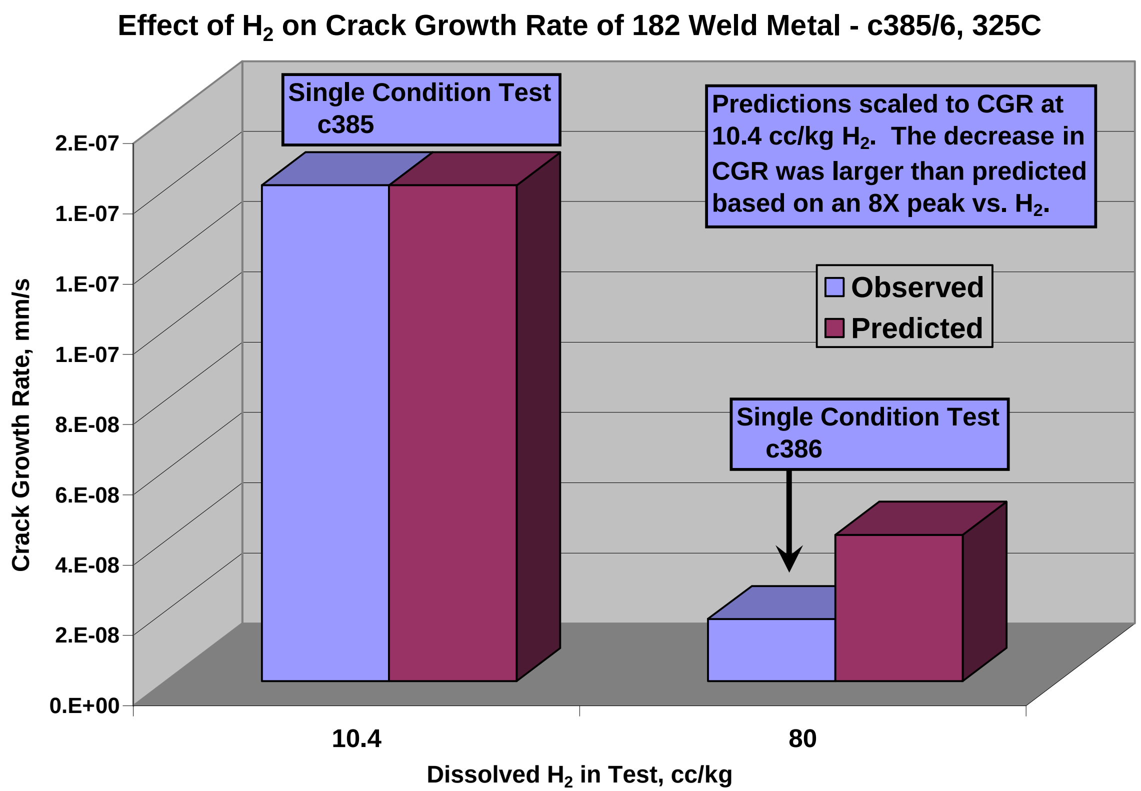
H_2 Effects on SCC of Alloy 182 Weld

c385, 10.4 cc/kg H2 – more nucleation and more crack advance.



c386, 80 cc/kg H2 – lower nucleation and less crack advance
Note Ni-metal stability gives shiny fracture.

H_2 Effects on SCC of Alloy 182 Weld



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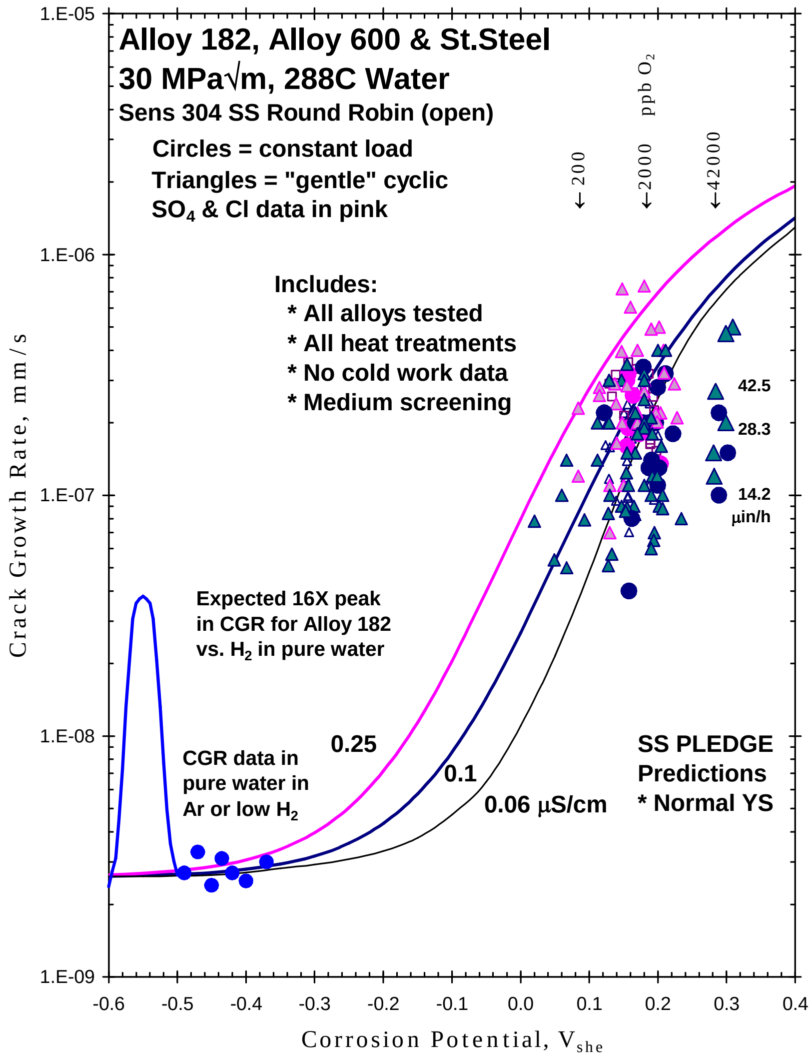
Role of H_2 and B/Li/pH Water Chemistry



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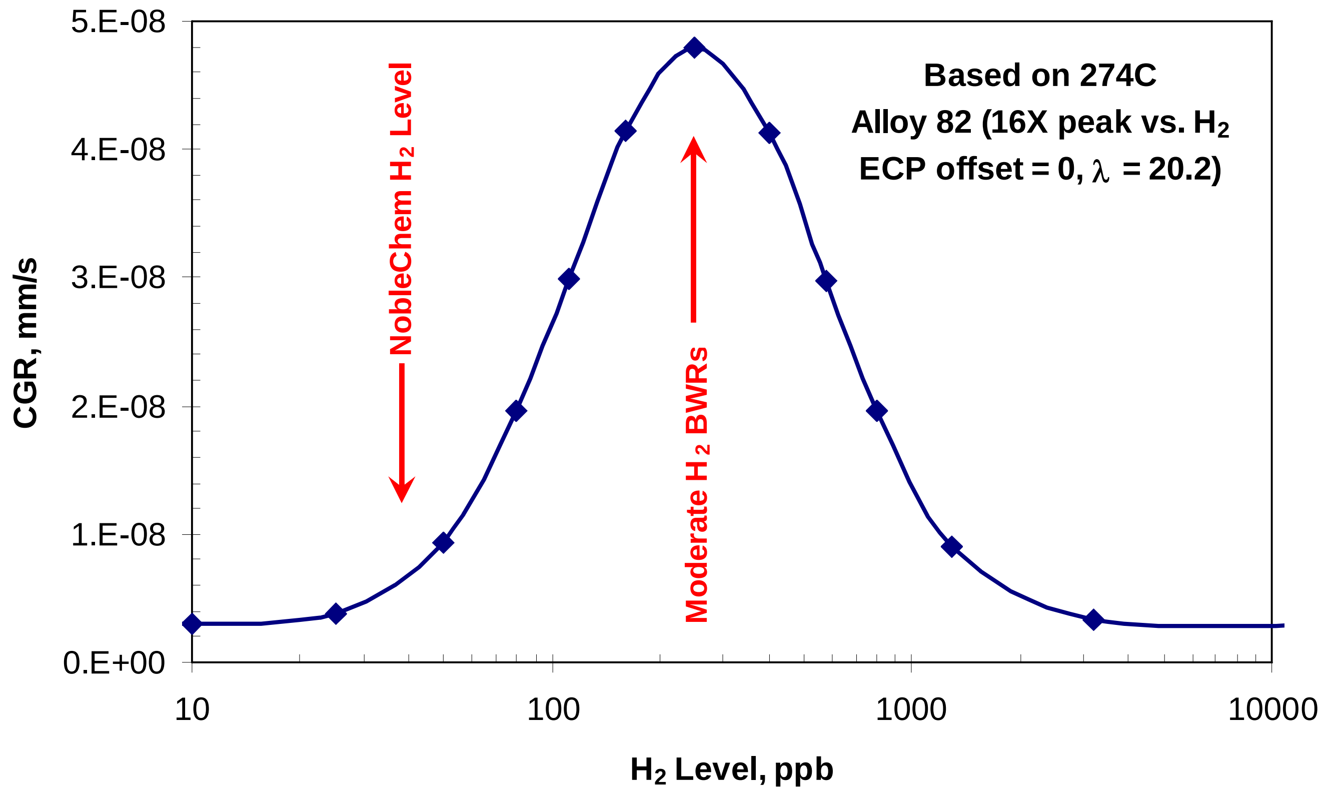
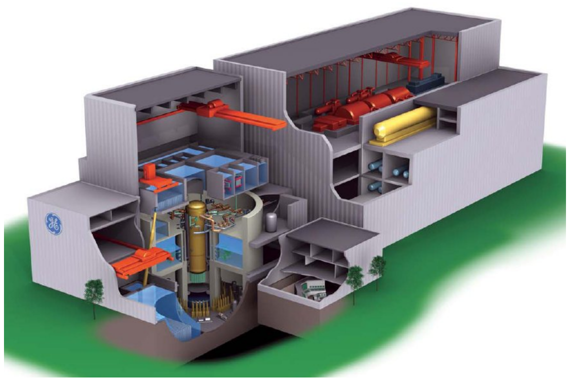
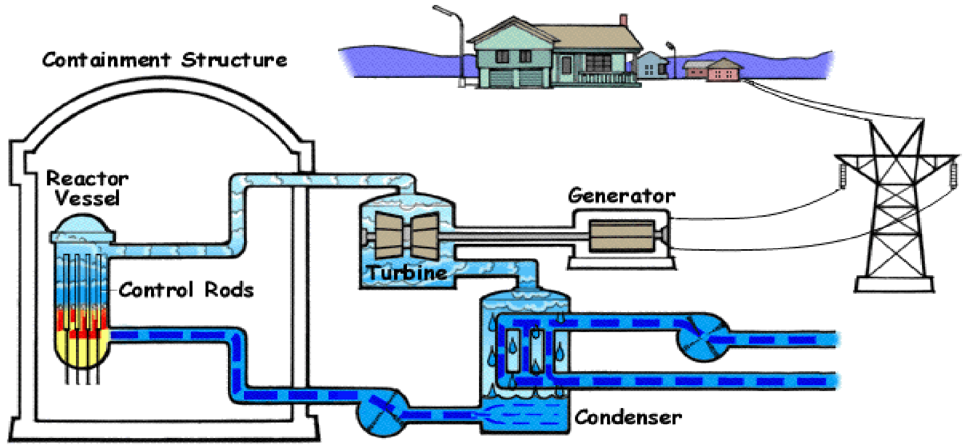


Peak growth rate occurs at much lower H_2 at 274C of BWR materials

Summary & Conclusions





- SS and Ni-base alloys and weldments are susceptable to SCC in both PWRs and BWRs
  - Demand on materials will increase with increased power rating
- PWR and BWR water chemistry have similar effects on crack growth
  - H_2 effect is dominant at low potentials
- Effective mitigation method for IASCC is not known
- Material processing and alloy chemistry important for SCC resistance
- Surface residual strain must be reduced to minimize crack

Questions?